Volume 15 Number 8 2004 ISBN 1-84544-046-3 ISSN 1741-038X

Journal of Manufacturing Technology Management

Formerly Integrated Manufacturing Systems

Logistics and supply chain management with artificial intelligence techniques – Part 1

Guest Editor: Dr Felix Chan

Emerald

www.emeraldinsight.com

VISIT…

LANZAROTE Caliente.com

Journal of Manufacturing Technology Management

Volume 15, Number 8, 2004 ISSN 1741-038X

Logistics and supply chain management with artificial intelligence techniques – Part 1

Guest Editor: Dr Felix Chan

Contents

Access this journal online

www.emeraldinsight.com/jmtm.htm

As a subscriber to this journal, you can benefit from instant, electronic access to this title via Emerald Fulltext. Your access includes a variety of features that increase the value of your journal subscription.

How to access this journal electronically

To benefit from electronic access to this journal you first need to register via the Internet. Registration is simple and full instructions are available online at **www.emeraldinsight.com/rpsv/librariantoolkit/emeraldadmin** Once registration is completed, your institution will have instant access to all articles through the journal's Table of Contents page at **www.emeraldinsight.com/1741-038X.htm** More information about the journal is also available at **www.emeraldinsight.com/jmtm.htm**

Our liberal institution-wide licence allows everyone within your institution to access your journal electronically, making your subscription more cost effective. Our Web site has been designed to provide you with a comprehensive, simple system that needs only minimum administration. Access is available via IP authentication or username and password.

Key features of Emerald electronic journals

Automatic permission to make up to 25 copies of individual articles
This facility can be used for training purposes, course notes, seminars etc. This only applies to articles of which Emerald owns copyright. For further details visit **www.emeraldinsight.com/copyright**

Online publishing and archiving
As well as current volumes of the journal, you can also gain access to past volumes on the internet via Emerald Fulltext. You can browse or search the database for relevant articles.

Key readings
This feature provides abstracts of related articles chosen by the journal editor, selected to provide readers with current awareness of interesting articles from other publications in the field.

Reference linking
Direct links from the journal article references to abstracts of the most influential articles cited. Where possible, this link is to the full text of the article.

E-mail an article
Allows users to e-mail links to relevant and interesting articles to another computer for later use, reference or printing purposes.

Additional complementary services available

Your access includes a variety of features that add to the functionality and value of your journal subscription:

E-mail alert services
These services allow you to be kept up to date with the latest additions to the journal via e-mail, as soon as new material enters the database. Further information about the services available can be found at **www.emeraldinsight.com/usertoolkit/emailalerts**

Emerald WIRE (World Independent Reviews)
A fully searchable subject specific database, brought to you by Emerald Management Reviews, providing article reviews from the world's top management journals.

Research register
A web-based research forum that provides insider information on research activity world-wide located at **www.emeraldinsight.com/researchregister** You can also register your research activity here.

User services
Comprehensive librarian and user toolkits have been created to help you get the most from your journal subscription. For further information about what is available visit **www.emeraldinsight.com/usagetoolkit**

Choice of access

Electronic access to this journal is available via a number of channels. Our Web site **www.emeraldinsight.com** is the recommended means of electronic access, as it provides fully searchable and value added access to the complete content of the journal. However, you can also access and search the article content of this journal through the following journal delivery services:

EBSCOHost Electronic Journals Service
ejournals.ebsco.com

Huber E-Journals
e-journals.hanshuber.com/english/index.htm

Ingenta
www.ingenta.com

Minerva Electronic Online Services
www.minerva.at

OCLC FirstSearch
www.oclc.org/firstsearch

SilverLinker
www.ovid.com

SwetsWise
www.swetswise.com

Emerald Customer Support

For customer support and technical help contact:
E-mail **support@emeraldinsight.com**
Web **www.emeraldinsight.com/customercharter**
Tel +44 (0) 1274 785278
Fax +44 (0) 1274 785204

Abstracts & keywords

Performance measurement and evaluation of suppliers in supply chain: an evolutionary fuzzy-based approach

Rajkumar Ohdar and Pradip Kumar Ray

Keywords Supplier evaluation, Supply chain management

In order to ensure the uninterrupted supply of items, the purchasing manager needs to evaluate suppliers' performance periodically. The evaluation process typically consists of identifying the attributes and factors relevant to the decision, and measuring the performance of a supplier by considering the relevant factors. Linguistic assessment of suppliers may be carried out based on several criteria. In this paper, an attempt has been made to evaluate the suppliers' performance by adopting an evolutionary fuzzy system. One of the key considerations in designing the proposed system is the generation of fuzzy rules. A genetic algorithm-based methodology is developed to evolve the optimal set of fuzzy rule base, and a fuzzy inference system of the MATLAB fuzzy logic toolbox is used to assess the suppliers' performance. The proposed methodology, illustrated with the data collected in a process plant, provides acceptable results in determining the suppliers' performance score.

Evaluation of the supplier performance using an evolutionary fuzzy-based approach

Vipul Jain, M.K. Tiwari and F.T.S. Chan

Keywords Supply chain management, Supplier evaluation

Different entities in a supply chain network operate in a highly interdependent environment when it comes to improving performance of the network in terms of objectives such as delivery performance, quality assurance and cost minimization, etc. In this research, an attempt has been made to evaluate the supplier performance by adopting evolutionary fuzzy system owing to the linguistic nature of the attributes associated with the suppliers and manufacturing units. The proposed methodology offers consistently good performance when applied to a variety of standard problems related to evaluation of supplier's performance available in the literatures.

Multi-agent architecture for supply chain management

Daniel Roy, Didier Anciaux, Thibaud Monteiro and Latifa Ouzizi

Keywords Supply chain management, Strategic planning, Virtual organizations

The purpose of this paper is to propose a new approach for the supply chain management. This approach is based on the virtual enterprise paradigm and the usage of multi-agent concept. The base component of our approach is a virtual enterprise node (VEN). The supply chain is viewed as a set of tiers (corresponding to the levels of production), in which each partner of the supply chain (VEN) is in relation with several customers and suppliers. Each VEN belongs to one tier. The main customer gives global objectives (quantity, cost and delay) to the supply chain. The mediator agent (MA) is in charge to manage the supply chain in order to respect those objectives as global level. Those objectives are taking over to negotiator agent at the tier level (NAT). This architecture allows supply chains management which is completely transparent seen from simple enterprise of the supply chain. The use of multi-agent system allows physical distribution of the decisional system. Moreover, the hierarchical organizational structure with a decentralized control guarantees, at the same time, the autonomy of each entity and the whole flexibility.

Supply chain scheduling using distributed parallel simulation

Juha-Miikka Nurmilaakso

Keywords Supply chain management, Production scheduling, Simulation

In a supply chain, an order often connects a number of companies whose schedules affect the success of the order. This paper proposes distributed supply chain scheduling in the agent architecture instead of centralised supply chain scheduling.
The companies communicate through their agents that share only the information relevant to the supply chain scheduling. This scheduling relies on distributed parallel forward simulation in which simple messages are exchanged between the agents periodically. According to these messages, each agent simulates the production orders of its

 · ISSN 1741-038X

company and receives and sends messages about the purchase and sale orders. This synchronises the simulation of the agent with the simulations of the other agents. Distributed simulation reduces the competitor's opportunities to manipulate the company's performance through the schedules of its suppliers and customers. Although distributed simulation does not optimise the schedules, it is capable of finding feasible schedules.

A decision support system to facilitate resources allocation: an OLAP-based neural network approach

H.C.W. Lau, A. Ning, W.H. Ip and K.L. Choy

Keywords Decision support systems, Resource allocation, Neural nets, Artificial intelligence

The emergence of advanced information technologies strengthens the capability to the entrepreneur to manage and manipulate data. However, the quality of information, the capability of providing the right information to the right person, and the utilization of information are still in doubt. Therefore, increasing numbers of firms have realized and started to develop as well as improve their existing information systems to fit the ever-changing business needs of the organization to support decision-making for the volatile business environment. Indeed, previous research studies have found that logistics management is the great frontier of cost reduction. Therefore, in this paper, an infrastructure of a decision support system is proposed to capture and maintain the business and resources allocation information with the adoption of the neural network for its artificial intelligent characteristic that mimic the operation of human brain to generate solutions systematically.
The proposed system is adopted by a shipping company to assist allocation of containers.

An object-based relational data base system using re-configurable finance and material objects

W.H. Ip, Bocheng Chen, Henry Lau and Wangqi Sunjing

Keywords Logistics, Resource allocation, Databases, Manufacturing resource planning

Any manufacturing information system today must be able to both "reconfigure" and "reengineer" operations in a cost-effective way. The objective of this paper is to propose an enterprise resource planning (ERP) system based on the re-configurable characteristics of material objects (MO) and finance objects (FO).
The implementation of this information system is based on the object technologsy concept, which composes enterprise applications in reusable software components made up of relevant manufacturing data. By analyzing the factors and the methods of integration of MO and FO, it can be shown that the proposed approach is more appropriate for the design and implementation of an ERP system, and that it is particularly suitable for small and medium-sized enterprises (SMEs).
The results demonstrate a flattened organizational structure, better communication, and enhanced workflow reconfiguration.

Collaborative supply chain planning using the artificial neural network approach

Matthew Chiu and Grier Lin

Keywords Supply chain management, Neural nets, Manufacturing resource planning

The purpose of this paper is to show how the concepts of collaborative agents and artificial neural networks (ANNs) can work together to enable collaborative supply chain planning (SCP). An agent-based supply chain network is decomposed into multiple ANNs in a way that the actual customer requirements and the agents' goals and constraints are matched in different stages. An error-minimising algorithm which models the agents' collaboration mechanism is used to train three ANNs, namely the supply net, the production net and the delivery net, for pursuing complete order fulfilment across the supply chain. In the example problem, the collaborative SCP paradigm is applied to determine the supply plan of an alliance of small firms, which provides assemble-to-order goods with short delivery lead-time to a regional market. The calculation results showed that the ANN approach achieved complete order fulfilment and significantly increased the resource utilisation of all supply chain agents.

Guest editorial

Guest Editor
Felix Chan

About the Guest Editor

Felix Chan is an Associate Professor in the Department of Industrial and Manufacturing Systems Engineering at the University of Hong Kong, having moved from the School of Manufacturing and Mechanical Engineering, University of South Australia in October 1996. His current research interests are logistics and supply chain management, distribution coordination with artificial intelligence techniques, systems modelling and simulation. To date, he has published over 250 research articles in referred international journals and international conference proceedings. He is a senior member of the Society of Manufacturing Engineers, and a member of the Chartered Institute of Logistics and Transport. He also serves as editorial member for several international journals including *International Journal of Computer Applications in Technology; International Journal of Business Performance Management; Pakistan Journal of Applied Sciences;* and *Supply Chain Management: an International Journal*. Dr Chan is also the invited Guest Editor-in-Chief, *International Journal of Business Performance Management* for a special issue on "Logistics and Supply Chain Performance Measurement", 2006.

A product is valuable only when it can be delivered to the user/customer at the right time, to the right place, and with the right quality. This is particularly essential in today's e-commerce environment, which demands quick response, and short product life cycle. Deviation of deliveries from the promised schedule can induce extra costs, which may be tangible like penalty costs, high inventory level and loss of market share or intangible like product depreciation, interruption of production and poor customer satisfaction. Efficient coordination of material suppliers, manufacturing plants, wholesalers, retailers, warehouses, and distribution centres, to deliver products as scheduled is the ultimate goal of supply chain management (SCM). In this connection, many industrialists and academicians are keen to develop optimization methodologies with artificial intelligence (AI) techniques that can optimize demand allocation problems, transportation policy, inventory management, etc.

This special issue on "Logistics and SCM with AI Techniques" aims to present the recent developments and applications concerning global optimization with AI techniques for logistics and SCM. The papers selected for this issue comprise a cross-section of topics that reflect a variety of perspectives and disciplinary backgrounds covering performance measurement of supply chains; supplier evaluation; multi-agent design for SCM; supply chain scheduling and simulation; collaborative supply chain planning; resources allocation; and database systems. I believe the seven papers presented in this special issue adequately reflect these topics.

The first paper, by Ohdar and Ray is a challenging problem in SCM, which relates to the performance measurement and evaluation of suppliers in supply chains. A genetic algorithm (GA) based methodology has been developed to evolve the optimal set of fuzzy rule-based system. The proposed methodology has been found to provide acceptable results in determining the suppliers' performance score.

The following paper by Jain *et al.*, also tackles the problem in the evaluation of supplier performance, with evolutionary fuzzy system. The proposed methodology offers consistently good performance when applied to some benchmarking problems in the literature.

The third paper by Daniel *et al.*, presents a new approach for the SCM. This approach is based on the virtual enterprise paradigm and the application of multi-agent concept. The proposed architecture allows SCM to become more transparent to other participating members in the supply chain.

The fourth paper by Nurmilaakso, proposes a methodology in the supply chain scheduling. This

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 721–722
 · ISSN 1741-038X

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 721–722

proposed scheduling methodology relies on distributed parallel forward simulation in which simple messages are exchanged between the agents periodically. Nurmilaakso concluded that although the proposed distributed simulation methodology could not optimise the schedules, at least it is capable of determining a feasible schedule for the practical implementation.

In the fifth paper by Lau *et al.*, the authors argue that the quality of information; the capability of providing the right information to the right person; and the utilisation of information in SCM are still immature. In this connection, they propose an infrastructure of a decision support system to aid to capture and maintain the business and resources allocation information, with the adoption of neural network concept. The proposed system is implemented in a shipping company to assist the allocation of containers.

This is followed by a paper by Ip *et al.*, which emphasises that the major characteristics of today's manufacturing information system must be able to both reconfigure and re-engineer operations in a cost-effective way. The authors propose an enterprise resource planning system based on the reconfigurable characteristics of material objects and finance objects. The results of a small case study demonstrated that the flattened organisational structure achieved a better communication and enhanced workflow reconfiguration.

The final paper of this first special issue by Chiu and Lin, demonstrates how the concepts of collaborative agents and artificial neural networks (ANNs) can work together to enable collaborative supply chain planning in this global era. An error-minimising algorithm which models the agents' collaboration mechanism is used to train three ANNs. With a demonstrated example, the results showed that the ANN approach achieved complete order fulfilment and dramatically improved the resource utilisation of all the supply chain agents.

I find great pleasure to announce that this special issue has attracted a great attention and response from researchers in the area of SCM. In order to accommodate all these good quality papers, there will be an additional issue dedicated to publish the second batch of accepted papers. In particular, these papers constitute state-of-the-art research-based contributes in the field of logistics and SCM with AI techniques. I sincerely hope you find the papers as useful and interesting as I did. I look forward to seeing another technological breakthrough in this area in the near future.

Performance measurement and evaluation of suppliers in supply chain: an evolutionary fuzzy-based approach

Rajkumar Ohdar and Pradip Kumar Ray

The authors

Rajkumar Ohdar and **Pradip Kumar Ray** are based at the Indian Institute of Technology (IIT), Kharagpur, India.

Keywords

Supplier evaluation, Supply chain management

Abstract

In order to ensure the uninterrupted supply of items, the purchasing manager needs to evaluate suppliers' performance periodically. The evaluation process typically consists of identifying the attributes and factors relevant to the decision, and measuring the performance of a supplier by considering the relevant factors. Linguistic assessment of suppliers may be carried out based on several criteria. In this paper, an attempt has been made to evaluate the suppliers' performance by adopting an evolutionary fuzzy system. One of the key considerations in designing the proposed system is the generation of fuzzy rules. A genetic algorithm-based methodology is developed to evolve the optimal set of fuzzy rule base, and a fuzzy inference system of the MATLAB fuzzy logic toolbox is used to assess the suppliers' performance. The proposed methodology, illustrated with the data collected in a process plant, provides acceptable results in determining the suppliers' performance score.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 723–734

ISSN 1741-038X
DOI 10.1108/17410380410565311

1. Introduction

In recent years, the concept of supply chain management (SCM), introduced to address the integration of organizational functions ranging from the ordering and receipt of raw materials through the manufacturing processes to the distribution and delivery of products to customers with a view to enable organizations to achieve higher quality in products and customer services with reduced inventory cost, has attracted considerable managerial attention because of its huge potential competitive impact (Stevens, 1989). In today's global market place, individual firms no longer compete as independent entities with brand names, but work as a part of an integrated supply chain. As such, the ultimate success of the firm depends on its managerial ability to integrate and coordinate the intricate network of business relationships among supply chain partners (Lambert and Cooper, 2000).

In order to ensure the uninterrupted supply of items in a supply chain, more than one supplier or vendor should be available for each item. Periodic evaluation of supplier's quality is carried out to ensure the meeting of relevant quality standards for all the incoming items, and the essential requirements advocated for suppliers' selection are quality, cost, delivery, flexibility, and response (Li *et al.*, 1997).

Owing to the diverse and linguistic nature of supplier attributes, usually they need to be categorized prior to further analysis for which a cross-functional team is required to rate the supplier' attributes in linguistic descriptions, such as very low, low, medium, high, and very high. Linguistic assessment of suppliers is to be carried out based on several criteria, such as quality, response to special orders, delivery performance and price. Because of the imprecise nature of linguistic attributes associated with suppliers, inconsistencies in the assessment of the levels of criteria are likely to affect the grading of supplier performance. To deal with these inconsistencies, a fuzzy-based approach is needed to convert the suppliers' linguistic attributes into fuzzy numbers resulting in assessment of supplier performance using fuzzy arithmetic.

One of the key considerations in designing an "evolutionary" fuzzy system is the generation of the fuzzy rules and the membership functions for each fuzzy set. While dealing with a few input variables, the cross-functional teams are usually engaged in generating the fuzzy rules for several performance attributes. Since the number of fuzzy rules increases exponentially with increase in

Received: 23 June 2003
Accepted: 6 February 2004

number of input variables, it is difficult for a cross functional team to define a complete fuzzy rule base for a good decision support system. It is essential to develop a genetic algorithm (GA)-based methodology to evolve the optimal set of fuzzy rule base. Several researchers (Wang *et al.*, 1998; Yuan and Zhuang, 1996) recommend evolutionary fuzzy systems in the areas of data classification, prediction, and control problems.

In this paper, an evolutionary fuzzy-based methodology is developed for a precise and effective evaluation of suppliers' performance. It maintains a population of fuzzy rule sets with their membership functions, and uses the GA to evolve a feasible fuzzy rule base. The proposed evolutionary fuzzy algorithm is used to generate the optimum number of fuzzy rule-base with adoption of fuzzy inference system (FIS) of the MATLAB fuzzy logic toolbox platform to assess the suppliers' performance for a process plant.

2. Supplier performance models: a brief overview

Literature in the area of supplier evaluation abounds primarily in three methodological streams, namely conceptual, empirical, and modeling. Since this paper approaches the problem mainly from a modeling perspective, the detailed discussion is limited to existing modeling research pertaining to supplier evaluation.

Dickson (1966), while studying the importance of supplier evaluation criteria for purchasing manager, presents more than 20 supplier attributes that a manager may consider in supplier evaluation, and concludes that cost, quality, and delivery performance are the three most important criteria in supplier evaluation. Analytical models for supplier evaluation range from simple weighted scoring models to complex mathematical programming approaches. In a comprehensive review of supplier selection and performance evaluation methods, Weber *et al.* (1991) report that 47 of the 74 articles in the review utilize multiple criteria.

The limitations of the traditional supplier evaluation methods, such as categorical, weighted point, and cost ratio approaches, are mentioned in the literature (Soukup, 1997; Willis *et al.*, 1993). The primary issue associated with categorical and weighted point methods is the determination of appropriate weights in computing a composite index for supplier performance. Similarly, the cost ratio approach (Timmerman, 1986), which evaluates the cost of each factor as a percent of total purchases for the supplier, requires the development of a cost accounting system. Li *et al.* (1997) propose a supplier performance measure applying the concept of dimensional analysis, and suggest a standardized unitless rating (SUR) by combining the weighted average of qualitative and quantitative scores associated with each supplier.

The analytic hierarchy process (AHP) (Saaty, 1980) is a multi criteria decision-making (MCDM) method providing a framework to cope up with the multiple criteria situation. The AHP first structures the problem in the form of a hierarchy to capture the criteria, sub-criteria, and the alternatives. A pairwise comparison is done for all the criteria to determine their relative weights, and the alternatives are compared with regard to each criterion. Finally, it determines a final score for each alternative. Narasimhan (1983) proposes an AHP-based methodology for supplier selection and performance evaluation. Tam and Tummala (2001) discuss the application of AHP in supplier selection and performance evaluation of a telecommunication system. Lee *et al.* (2001) propose an AHP-based supplier selection and management system (SSMS) that includes a purchasing strategy, a supplier selection, and supplier management systems, and explain how SSMS is applied to real supply chain. Ghodsypour and Brien (1998) propose both AHP and linear programming techniques to assess both qualitative and quantitative factors in the selection of the suppliers.

In recent years, several techniques for evaluating the performance of suppliers has been reported in the literature, notable among them being principal component analysis (PCA) (Petroni and Braglia, 2000), total cost of ownership (Ellram, 1995), human judgment models (Patton, 1996), interpretive structural modeling (Mandal and Deshmukh, 1994), discrete choice analysis experiments (Verma and Pullman, 1998), and neural networks (Siying *et al.*, 1997). The data envelopment analysis (DEA) (Narasimhan *et al.* 2001) for supplier evaluation and rationalization also incorporates multiple supplier inputs and outputs in determining the relative efficiencies. Kanan *et al.* (2002) describe the findings of an empirical study on supplier selection and assessment criteria of a manufacturing company wherein the importance of the so-called "soft" non-quantifiable selection criteria, such as suppliers' strategic commitment to a buyer, having a greater impact on performance than the so-called "hard" quantifiable criteria, such as supplier capability has been emphasized. Jeong and Lee (2002) propose a multi-criteria supplier selection (MCSS) model to deal with the supplier selection problems in the SCM, where a fuzzy-based methodology is used to assess the ratings for the

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

qualitative factors, such as profitability and quality. Muralidharan *et al.* (2002) also propose a multi-criteria group decision making model for supplier selection.

3. Evolutionary fuzzy systems

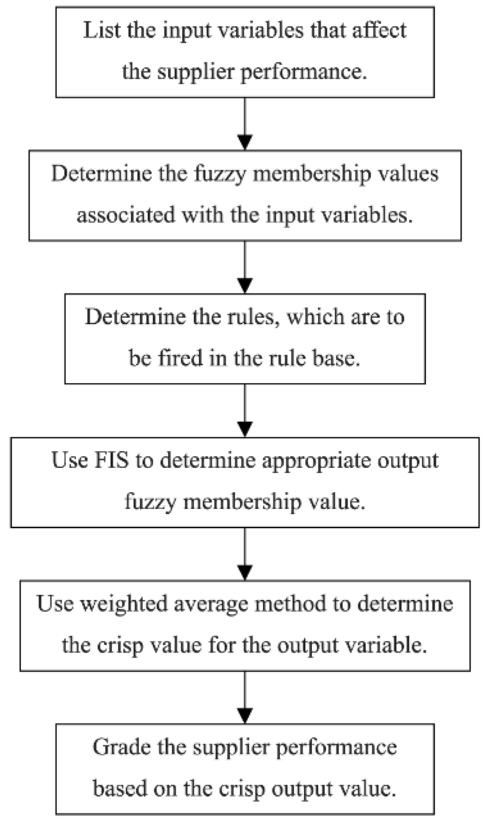
In many real-world applications, fuzzy systems that make use of linguistic rules are aptly suited to describe the behavior of the real-world problem, which is difficult to model mathematically (Zadeh, 1978). In the majority of the existing applications, the fuzzy rules with few input variables are generated by the experts and decision makers who are well-conversant with the problems. The possible number of fuzzy rules for a given system grows exponentially when the number of input variables increases. It is very difficult for an expert to define a complete "rule set" for assessing the system performance.

In several cases, the system performance improves by tuning the membership functions and selecting suitable fuzzification and defuzzification methods. For modeling the performance measurement and evaluation system for suppliers, an "evolutionary" fuzzy system has been employed in which the fuzzy rule set and the number of rules inside the rule set are generated using a GA. The GA has recently found its growing applications in solving the several types of linear and non-linear optimization problems (Goldberg, 1989; Davis, 1991). Many researchers use this algorithm or "meta-heuristic" for generation of a set of fuzzy rules required in designing the fuzzy rule base (Abey and Lan 1995). In this context, the constituents of the proposed evolutionary fuzzy system, as shown in Figure 1, for assessing suppliers' performance are as follows:
(1) concept of rule generation;
(2) representation;
(3) fitness function;
(4) crossover operator; and
(5) mutation operator

3.1 Concept of rule generation

The basic idea of the rule generation process is to apply a relevance test to single IF/THEN statements to assess their ability to describe a relevant aspect of the system under consideration. This allows getting transparent and comprehensive rule bases, and reduces the problem of finding a good rule base to the much smaller problem of finding single relevant rules. Instead of complete rules that consider every input variable in each premise, generalizing rules are used that consider only a part of the input variables in the premise.

Figure 1 System flow chart for assessing supplier's performance based on evolutionary fuzzy system



The advantage of generalizing rules is that they cover not only one, but also several input situations, and therefore, fewer rules are necessary to design the fuzzy rule base.

3.2 Representation

The first important consideration while designing a fuzzy expert system using GA is the representation strategy adopted to encode the fuzzy system into the chromosome. A fuzzy system is well defined only when the fuzzy rule base and the membership functions associated with each fuzzy set of a variable are specified. Thus, it is practically realized that to represent a fuzzy expert system completely, each chromosome must encode all the requisite information about the rule sets and the membership functions. For a fuzzy system with five input variables and one output variable, each variable (input/output) has five fuzzy sets representing the linguistic description: very low, low, medium, high, and very high. The fuzzy sets corresponding to each input or output may be represented by the integers 1-5, where integer "0" represents the absence of a term. In this way, a fuzzy rule can be represented by six integers. Consider an example rule for which input 1 is high, input 2 very high, input 3 medium, input 5 very

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

low and output low, the generalized rule can be encoded as 4 5 3 0 1 2. If a rule base includes 20 rules, an integer string of length 120 can represent the rule set completely.

In this paper, four variables with each having five fuzzy sets are considered to estimate the supplier performance score. The fuzzy set membership functions: trapezoidal, triangle, triangle, triangle, and trapezoidal functions correspond to the fuzzy sets of input variables, namely, very low, low, medium, high, and very high, respectively. The start and end of the membership functions are fixed as per the range of the input variables. For the output variable, all the fuzzy sets are represented by triangular membership functions owing to their simplicity in computation. By encoding the plant-specific data into a triangular and trapezoidal membership functions, provide reasonably acceptable results.

The fuzzy rules in the rule base and the number of such fuzzy rules that are associated with the problem are to be evolved using GA. In order to reduce the search space, it is advocated that the maximum number of rules concerning any problem is fixed in advance (Tiwari and Roy, 2002). The maximum number of acceptable rules considered in this study is set to 40 as it gives the best fitness value. Thus, the total length of the chromosome representing the system is $1 + 5 \times (40) = 201$ and the system can be represented as follows:

$$S_1 S_2 S_3 S_4 S_5 S_6 \ldots S_{57} S_{58} S_{59} \ldots S_{140} S_{141} \ldots S_{199} S_{200} S_{201}, \tag{1}$$

where, S_1 represents the number of rules varying between 1 and 40, $S_2, S_3, \ldots, S_6$ encode the first fuzzy rule in the rule set, and $S_{197}, S_{198}, \ldots, S_{201}$ represents the last fuzzy rule in the rule set, and S_1 denotes the number of possible rules that are used to design the rule base. However, in a given situation, each rule may not be feasible. A rule with a zero antecedent or consequent part is an infeasible rule and should be excluded from the fuzzy rule base. In order to ensure that the chromosome contains no infeasible rules, the fitness value corresponding to the chromosome is assigned to a very small floating number (0, 1) so that these chromosomes do not pass over to the next generation.

3.3 Fitness function

While the genotype (internally-coded inheritable information) representation encodes the rule base into an integer string, the fitness function evaluates the performance of the rule base. For prediction and estimation problems, the mean-square error or absolute difference error related function is most commonly used. In this case of supplier performance evaluation modeling, the mean square error function is used to evaluate the fitness of the chromosomes owing to its suitability in prediction and estimation problems as supplier performance evaluation is like an estimation problem.

The mean square error, E is given by

$$E = \frac{1}{N}\left(\sum_{i=1}^{N}(o_i - e_i)^2\right) \tag{2}$$

where N is the number of evolved fuzzy rules, and o_i and e_i the actual and the expected output, respectively. The procedure for determining expected output value is given in Appendix. The fitness value is given as

$$\text{Fitness value} = \frac{1}{(1+E)} \tag{3}$$

Chromosomes with higher fitness value are carried to the next generation.

3.4 Crossover operator

Crossover is a process by which two parent strings recombine to produce two new offspring strings. An overall probability is assigned to the crossover process. Given two parent chromosomes, the algorithm invokes crossover only if a randomly generated number in the range of 0-1 is greater than the crossover rate, otherwise the strings remain unaltered. This probability is often considered to be lying in the range of 0.65-0.80 (Tiwari and Roy, 2002). Two-point crossover probability is used in this case with a probability in the range of 0.75-0.90.

3.5 Mutation operator

After crossover, strings are usually subjected to mutation. A mutation operator randomly alters few composition of a string to produce a new offspring instead of recombining two strings. In a traditional GA, mutation of a bit involves flipping it, i.e. changing a "0" to "1" or vice versa. It is found that the chromosome representing the fuzzy system is integer-based instead of binary based, i.e. each element of the string has an integer range representing the various states of the variable (input and output). The mutation operator used is thus different than that used in binary encoding. Each time an element is chosen for mutation, which is increased or decreased by replacing it by an integer in the range [1, 5] excluding the present value of the element. The integers of the string are independently mutated, i.e. the mutation of the element does not influence the probability of mutation of another element.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

4. Fuzzy rule base generation

The implementation of an evolutionary fuzzy system for generation of an optimal fuzzy rule base is written in C and compiled in Borland C compiler. A case study data from a process industry is provided to demonstrate the efficacy of the proposed algorithm.

The supplier performance is graded based on the attributes, which are selected from both the supplier and manufacturer's viewpoints. Quality, delivery, service, and price are considered to be the attributes. To evolve the fuzzy rule base using GA, an appropriate fitness function is essential. Here, a mean square error function is adopted for fitness measurement, where the expected outputs are determined by prioritizing the attributes. Each feasible fuzzy rule that is evolved in the rule base has the maximum prioritized attribute in the first position, the next prioritized attribute in the second position, and so on. These priorities are analogous to weights that are assigned to the attributes, indicating their relative importance.

The fuzzy membership functions associated with the fuzzy sets of each input are left triangle, triangle, triangle, triangle, and right triangle corresponding to the linguistic descriptions very low, low, medium, high, and very high. The ranges and the overlap areas of the membership functions are fixed. A triangular fuzzy membership function has been adapted to represent the fuzzy sets of the output variable. Figure 2 shows the various membership functions for denoting the fuzzy sets for the input and output variables.

The fuzzy rule base is designed through simulation by varying different GA parameters, namely crossover and mutation probability. The number of generations and the population in the GA run are considered to be 50 and 15, respectively. Simulation result shows that the optimum fitness value for the chromosomes approaches a maximum value of 0.552 for a crossover probability of 0.90 and mutation probability of 0.08. The fitness value versus generation graphs for three different GA runs to evolve the optimum set of fuzzy rules for estimating the supplier performance are shown in Figure 3.

5. Fuzzy inference system

A fuzzy-rule based inference system comprises three basic units, namely fuzzifier, inference engine, and defuzzifier (Ross, 1995). The primary function of the system is to establish a mapping from inputs to outputs. However, this mapping mechanism is not built on any precisely defined analytical or numerical function. Instead, it is constructed on human knowledge: As experience and intuitions are often represented in natural languages in the form of (IF . . . THEN . . .) rules, it works just like an expert who reasons and inferences by using knowledge available to him or her. It is therefore called an inference engine that applies knowledge on the inputs and derives solutions as outputs. Figure 4 shows a schematic diagram of a FIS and fuzzy rule base generation using GA.

The input and output vectors of a generalized FIS, including state linguistic variables, may be defined as

$$\left.\begin{aligned} x &= \left\{\left(x_i, U_i, \left\{T^1_{x_i}, T^2_{x_i}, \ldots, T^{ki}_{x_i}\right\},\right.\right.\\ &\qquad \left.\left.\left\{\mu^1_{x_i}, \mu^2_{x_i}, \ldots, \mu^{ki}_{x_i}\right\}\right)\Big|_{i=1\ldots l}\right\},\\ y &= \left\{\left(y_i, U_i, \left\{T^1_{y_i}, T^2_{y_i}, \ldots, T^{ki}_{y_i}\right\},\right.\right.\\ &\qquad \left.\left.\left\{\mu^1_{y_i}, \mu^2_{y_i}, \ldots, \mu^{ki}_{y_i}\right\}\right)\Big|_{i=1\ldots m}\right\}, \end{aligned}\right\} \quad (4)$$

where x_i forms a fuzzy input space $U = U_1 \times U_2 \times \cdots \times U_l$, y_i forms a fuzzy output space $V = V_1 \times V_2 \times \cdots \times V_m$, $T(x_i) = \{T^1_{x_i}, T^2_{x_i}, \ldots, T^{ki}_{x_i}\}$ is the linguistic term set, $\mu(x_i) = \{\mu^1_{x_i}, \mu^2_{x_i}, \ldots, \mu^{ki}_{x_i}\}$ is the semantic membership function for $T(x_i)$, and $k_{\mathrm{i}} =$ number of linguistic terms for the input variable i.

The core of the inference engine is its knowledge, which is represented in the form of "if-then" rules. The fuzzy-rule base for the supplier performance assessment consists of a group of "if-then" rules with four inputs representing the four supplier selection variables and one output representing the supplier performance score shown below:

$$\mathrm{R}^1\text{: IF } x_1 \text{ is } A_1 \text{ AND } x_2 \text{ is } B_1 \text{ AND } x_3 \text{ is } C_1 \text{ AND } x_4 \text{ is } D_1\text{, THEN } y \text{ is } E_1,$$

$$\mathrm{R}^2\text{: IF } x_1 \text{ is } A_2 \text{ AND } x_2 \text{ is } B_2 \text{ AND } x_3 \text{ is } C_2 \text{ AND } x_4 \text{ is } D_2\text{, THEN } y \text{ is } E_2,$$

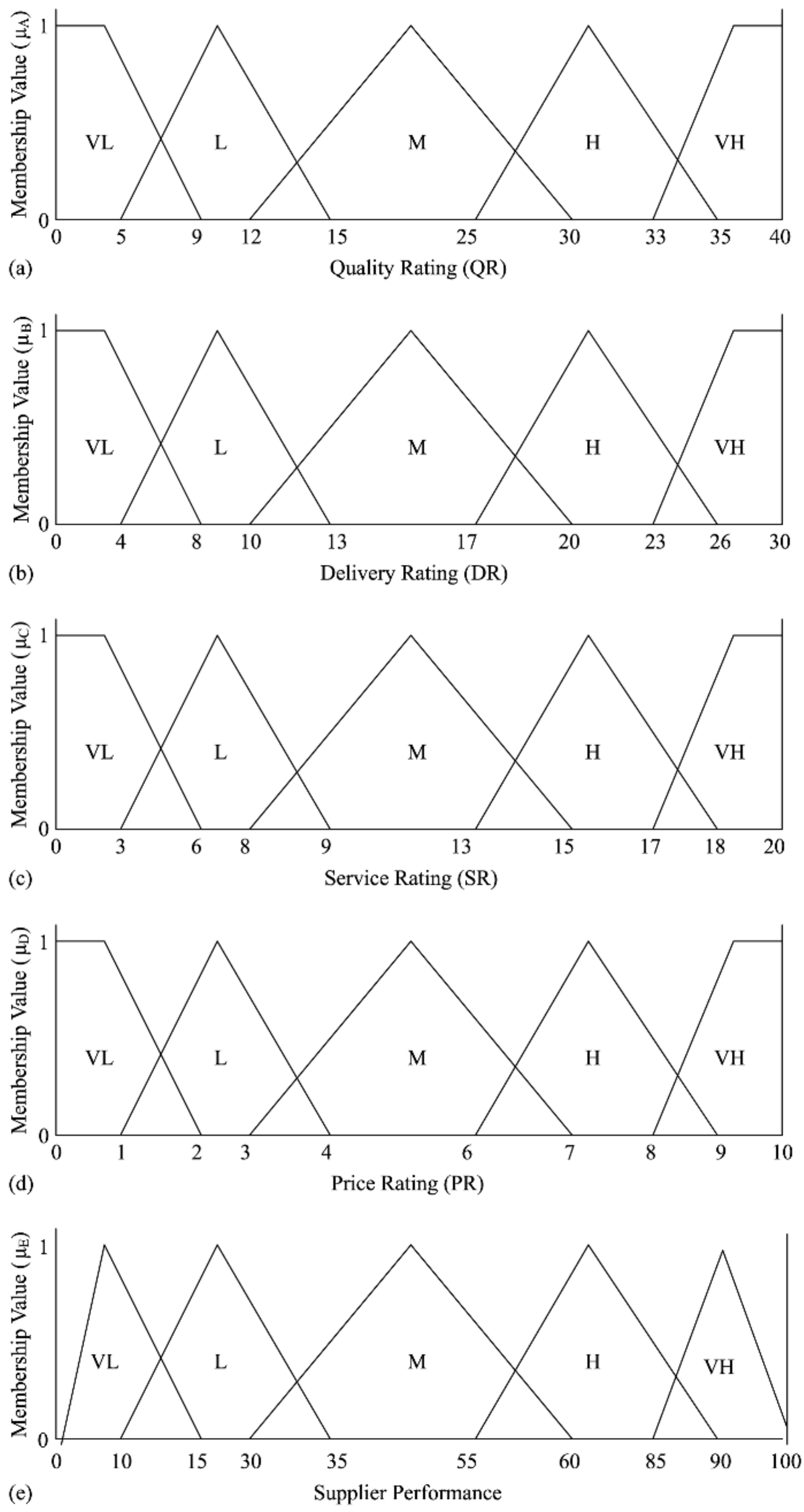
$$\vdots$$

$$\mathrm{R}^n\text{: IF } x_1 \text{ is } A_n \text{ AND } x_2 \text{ is } B_n \text{ AND } x_3 \text{ is } C_n \text{ AND } x_4 \text{ is } D_n\text{, THEN } y \text{ is } E_n,$$

A_i, B_i, C_i, D_i, and E_i are fuzzy subsets for the four inputs x_1, x_2, x_3, x_4, and one output y, which are all defined by the corresponding membership functions viz., μ_{A_i}, μ_{B_i}, μ_{C_i}, μ_{D_i} and μ_{E_i}.

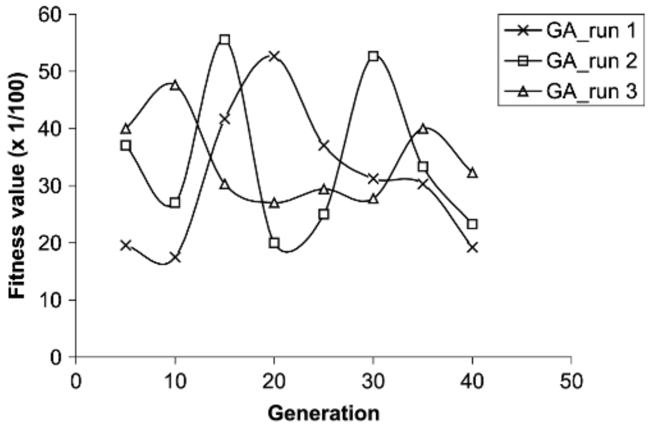
Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

Figure 2 Membership functions of input and output attributes of supplier performance



Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

Figure 3 Performance of GA with different crossover and mutation probabilities



Notes: GA_run 1: Crossover Prob. = 0.9, Mutation Prob. = 0.08,
GA_run 2: Crossover Prob. = 0.85, Mutation Prob. = 0.15,
GA_run 3: Crossover Prob. = 0.8, Mutation Prob. = 0.1

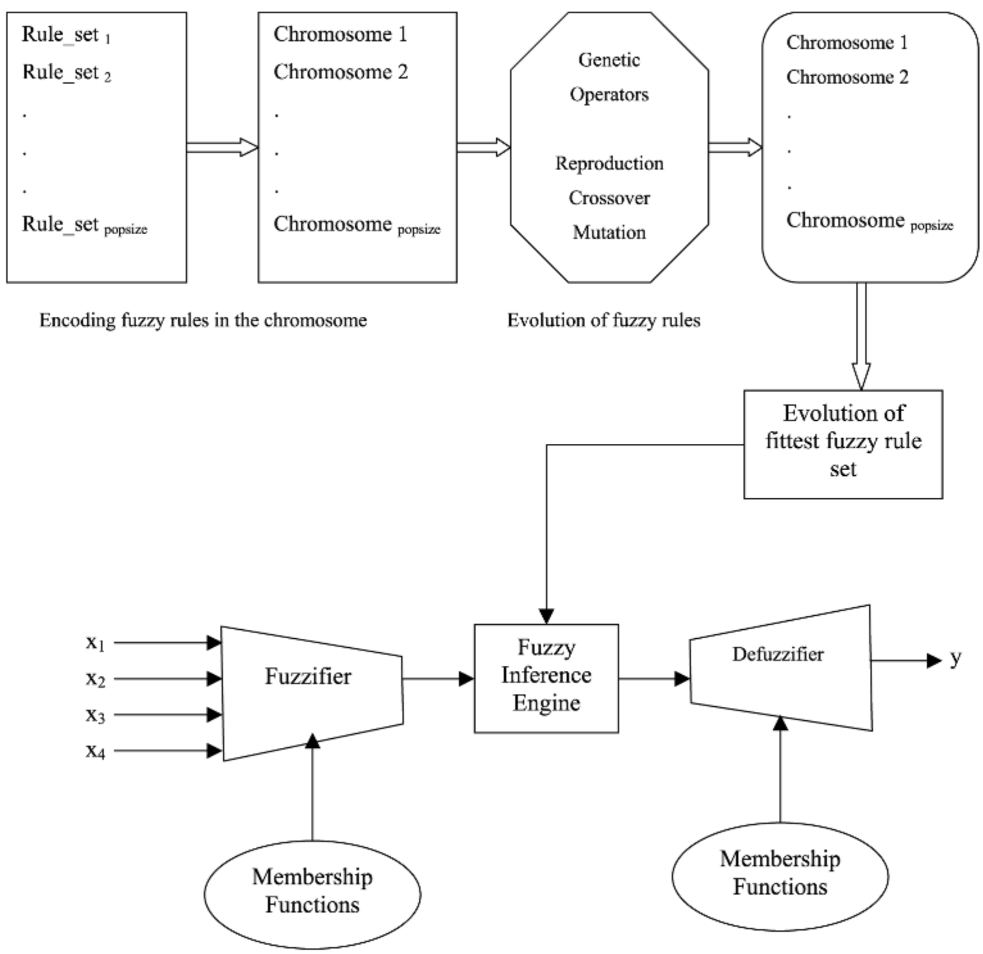
In this particular supplier performance evaluation method, 40 rules in total are generated by GA to represent system requirements and the knowledge of how the four performance attributes contribute to the overall performance of a supplier.

Mamdani's fuzzy implication rule (Lin and Lee, 1996) has been used for the inference logic. Basically, when the inference engine receives a set of inputs, it fuzzifies them to generate a set of fuzzy inputs. All the rules may be activated or fired to a certain degree, and they produce individual outputs accordingly. The individual outputs are combined together using "minimum-maximum" logic operation to produce the aggregated single fuzzy output. Finally, the fuzzy output is to be defuzzified to generate a digital or crisp output.

The attributes as the system's inputs are to be fuzzyfied for the fuzzy inference engine to work on them. Before fuzzification, the suppliers' attributes are just crispy numerical data carrying no linguistic value. Fuzzification involves assigning a set of predefined fuzzy membership functions to them so that the data are transformed into a set of meaningful observations for fuzzy inference engine.

To start with, the firing strengths of each rule are expressed as

Figure 4 System flow chart to illustrate the evolution of an optimum fuzzy rule base, and the fuzzy inference system



$$\left.\begin{aligned} \alpha_1 &= \mu_{A_1}(x_1) \wedge \mu_{B_1}(x_2) \wedge \mu_{C_1}(x_3) \wedge \mu_{D_1}(x_4) \\ \alpha_2 &= \mu_{A_2}(x_1) \wedge \mu_{B_2}(x_2) \wedge \mu_{C_2}(x_3) \wedge \mu_{D_2}(x_4) \\ &\vdots \\ \alpha_n &= \mu_{A_n}(x_1) \wedge \mu_{B_n}(x_2) \wedge \mu_{C_n}(x_3) \wedge \mu_{D_n}(x_4) \end{aligned}\right\} \quad (5)$$

The ith fuzzy inference rule leading to the ith reasoning decision (i.e. the individual fuzzy output) is represented as

$$\mu_{E_i'}(y) = \alpha_i \wedge \mu_{E_i}(y) \quad (6)$$

The final inferred fuzzy amalgamated consequent, E is given by

$$\begin{aligned} \mu_E(y) &= \mu_{E_1'} \vee \ldots \vee \mu_{E_n'} \\ &= [\alpha_1 \wedge \mu_{E_1}(y)] \vee \ldots \vee [\alpha_n \wedge \mu_{E_n}(y)], \quad (7) \end{aligned}$$

where $\wedge$ (AND) is the minimum operation, $\vee$ (OR) the maximum operation, and n the number of rules employed.

The defuzzification method used is called the weighted average method, which transforms the fuzzy inference output, $\mu_E(y)$ into a non-fuzzy value, y_0, which is expressed as

$$y_0 = \frac{\sum_{i=1}^{n} y\mu_{E_i}(y)}{\sum_{i=1}^{n} \mu_{E_i}(y)} \quad (8)$$

This non-fuzzy value (y_0) represents the supplier performance score.

6. Case study

The problem related to the determination of supplier performance is studied with reference to a case in a process plant located in the eastern region of India. The main product of the plant is graded pig iron, mainly used as a raw material in foundry. Besides the raw material suppliers, the company maintains a number of suppliers for its consumable and non-consumable items. The first objective of the management of the plant is to reduce and optimize the inventory of raw materials and consumable items, and the second objective is to reduce the size of the supplier base without compromising the acceptable service level. To achieve these objectives, the plant management is required to assess the supplier performance periodically based on a number of supplier attributes, viz., quality rating (QR), delivery rating (DR), service rating (SR), and price rating (PR) having weightage of 40, 30, 20, and 10 percent, respectively. The weightages are decided by a group of concerned personnel of the plant having adequate knowledge in dealing with the suppliers. The selected supplier attributes ratings are defined as follows:

(1)

$$\mathrm{QR} = \left(\frac{Q_1 + (0.7 \times Q_2)}{Q}\right) \times 40$$

where Q = total quantity supplied; Q_1 = quantity accepted and Q_2 = quantity accepted with concession/deviation,

(2)

$$\mathrm{DR} = \frac{\mathrm{PD}}{\mathrm{AD}} \times 30$$

where PD = promised delivery time in days, and AD = Actual delivery time in days.

(3) SR is determined by the subjective judgments of the purchasing manager, and is defined in the interval [0, 20].

(4)

$$\mathrm{PR} = \frac{\mathrm{LP}}{P} \times 10$$

where LP = lowest price in the same period, and P = supply price by the supplier.

The data on the attributes as mentioned for different suppliers are collected from the purchasing department during the period November-December 2002. A sample data set is shown in Table I.

The procedure for computing the performance score of a supplier using equations (4) to (8) is explained below.

As shown in equation (4), the linguistic variables x_i and y_i are modeled by fuzzy sets, $T(x_i)$ and membership functions, $\mu(x_i)$, which are expressed are as follows.

$$T(x_i) = \{T_{x_i}^1, T_{x_i}^2, \ldots, T_{x_i}^{ki}\}$$

is the linguistic term set, and

Table I Value of the suppliers' attributes for a sample of ten suppliers

	Suppliers' attributes			
Suppliers (S_i)	**QR (x_1)**	**DR (x_2)**	**SR (x_3)**	**PR (x_4)**
S_1	32	25	16	7
S_2	36	16	18	6
S_3	26	27	14	8
S_4	22	14	17	9
S_5	38	12	16	8
S_6	35	28	9	8
S_7	26	26	17	9
S_8	29	16	19	8
S_9	32	20	12	8
S_{10}	29	17	11	7

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

$$\mu(x_i) = \{\mu^1_{x_i}, \mu^2_{x_i}, \ldots, \mu^{ki}_{x_i}\}$$

is the semantic membership function for $T(x_i)$.

For the case example considered, the input variables for the supplier-1, as shown in Table I are: $x_1 = \mathrm{QR} = 32$; $x_2 = \mathrm{DR} = 25$; $x_3 = \mathrm{SR} = 16$; $x_4 = \mathrm{PR} = 7$.

Using equation (4), x_i for $i = 1, \ldots 4$ forms a fuzzy input space $U = U1 \times U2 \times U3 \times U4$ with intervals $U_1 = [0, 40]$, $U_2 = [0, 30]$, $U_3 = [0, 20]$, and $U_4 = [0, 10]$. y_i for $i = 1$ forms a fuzzy output space $V = V_1$ with the interval [0, 100].

For input variable, $x_1 = \mathrm{QR}$

$$T(x_1) = \left\{T^1_{x_1}, T^2_{x_1}, T^3_{x_1}, T^4_{x_1}, T^5_{x_1}\right\},$$

and

$$\mu(x_1) = \left\{\mu^1_{x_1}, \mu^2_{x_1}, \mu^3_{x_1}, \mu^4_{x_1}, \mu^5_{x_1}\right\} \quad \text{for} \quad i = 1; k_1 = 5$$

The linguistic term set activated and the membership functions for the attributes of the supplier-1 are shown in Table II.

Using equation (5), the rules activated for the supplier-1 are as follows:
Rule 1:
$\alpha_1 = \mu_{\mathrm{H}}(32) \wedge \mu_{\mathrm{H}}(25) \wedge \mu_{\mathrm{H}}(16) \wedge \mu_{\mathrm{H}}(7)$
$= \min\{3/5, 2/9, 2/3, 2/7\} = 2/9$
Rule 2:
$\alpha_2 = \mu_{\mathrm{H}}(32) \wedge \mu_{\mathrm{H}}(25) \wedge \mu_{\mathrm{VH}}(16) \wedge \mu_{\mathrm{H}}(7)$
$= \min\{3/5, 2/3, 2/3, 2/7\} = 2/7$

Using equation (6), the control outputs of the rules are given as

$$\alpha_1 \wedge \mu_{\mathrm{H}}(y) = \min(2/9, \mu_{\mathrm{H}}(y)),$$

and

$$\alpha_2 \wedge \mu_{\mathrm{VH}}(y) = \min(2/7, \mu_{\mathrm{VH}}(y))$$

Using equation (7), the aggregate fuzzy output is computed as

$$\mu_E(y) = [\alpha_1 \wedge \mu_{\mathrm{H}}(y)] \vee [\alpha_2 \wedge \mu_{\mathrm{VH}}(y)]$$

$$= \max\{\min(2/9, \mu_{\mathrm{H}}(y)),\ \min(2/7, \mu_{\mathrm{VH}}(y))\}$$

$\mu_E(y)$ is a union of two triangular fuzzy numbers high (H), and very high (VH), as shown in Figure 5.

Using equation (8), the performance score of the supplier-1 is computed as

$$y_0 = \frac{\mu_{E_1}(y) \times y_1 + \mu_{E_2}(y) \times y_2}{\mu_{E_1}(y) + \mu_{E_2}(y)}$$

or,

$$y_0 = \frac{\mu_{E_1}(y) \times \left(\frac{q_1+q_2}{2}\right) + \mu_{E_2}(y) \times \left(\frac{p_1+p_2}{2}\right)}{\mu_{E_1}(y) + \mu_{E_2}(y)}$$

or,

$$y_0 = \frac{\frac{2}{9} \times \left(\frac{58.89+86.11}{2}\right) + \frac{2}{7} \times \left(\frac{87.14+97.86}{2}\right)}{\frac{2}{9} + \frac{2}{7}}$$

or,

$$y_0 = \frac{16.11 + 26.43}{0.508} = 83.75$$

Similarly, the performance scores of other suppliers are computed using the same procedure. In this case, FIS of MATLAB fuzzy logic toolbox is used for computation of suppliers' performance scores. The details of the linguistic measures related to suppliers' attributes for different supplier are shown in Table III.

7. Results and discussion

Out of a total of 23 criteria selected for supplier performance measurement and evaluation model (Dickson, 1966), it is reported that the criteria such as quality, delivery, performance history, warranties and claim policies, product facilities and qualities, and price are most important. Lee *et al.* (2001) present the four main criteria for supplier selection and performance evaluation as quality, cost, delivery, and service divided in 12 sub-criteria in total. The case example discussed in

Figure 5 Aggregated fuzzy output

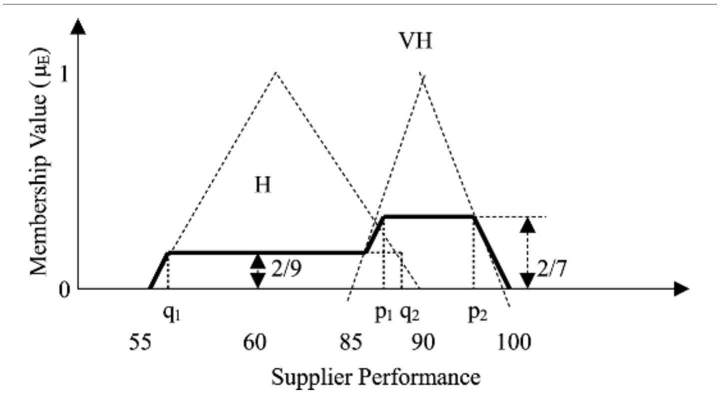


Table II Computation of membership value for the attributes of supplier-1

Attributes	Crisp data	Activated linguistic term set	Membership value
x_1 = QR	32	$T^4_{x_1}$ = high (H)	$\mu^4_{x_1} = \mu_H(32) = 3/5$
x_2 = DR	25	$T^4_{x_2}$ = high (H)	$\mu^4_{x_2} = \mu_H(25) = 2/9$
		$T^5_{x_2}$ = very high (H)	$\mu^5_{x_2} = \mu_{VH}(25) = 2/3$
x_3 = SR	16	$T^4_{x_3}$ = high (H)	$\mu^4_{x_3} = \mu_H(16) = 2/3$
x_4 = PR	7	$T^4_{x_4}$ = high (H)	$\mu^4_{x_4} = \mu_H(7) = 2/7$

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

Table III Linguistic measures related to suppliers' attributes and suppliers

	Suppliers' attributes			
Suppliers (S_i)	**QR (x_1)**	**DR (x_2)**	**SR (x_3)**	**PR (x_4)**
S_1	H (3/5)	H (2/9) VH (2/3)	H (4/5)	M (0) H(2/3)
S_2	VH (1)	M (4/5)	H (0) VH (1)	M (1/2) H (0)
S_3	M (4/9) H (1/5)	VH (1)	M (2/7) H (2/5)	H (2/3) VH (0)
S_4	M (8/9)	M (4/5)	H (2/5) VH (0)	H (0) VH (1)
S_5	VH (1)	L (2/9) M (2/5)	H (4/5)	H (2/3) VH (0)
S_6	VH (1)	VH (1)	L (0) M (2/7)	H (2/3) VH (0)
S_7	M (4/9) H (1/5)	H (0) VH (1)	H (2/5) VH (0)	H (0) VH (1)
S_8	M (1/9) H (4/5)	M (4/5)	VH (0)	H (2/3) VH (0)
S_9	H (3/5)	M (0) H(6/9)	M (6/7)	H (2/3) VH (0)
S_{10}	M (1/9) H (1/5)	M (3/5) H (0)	M (6/7)	M (0) H (2/3)

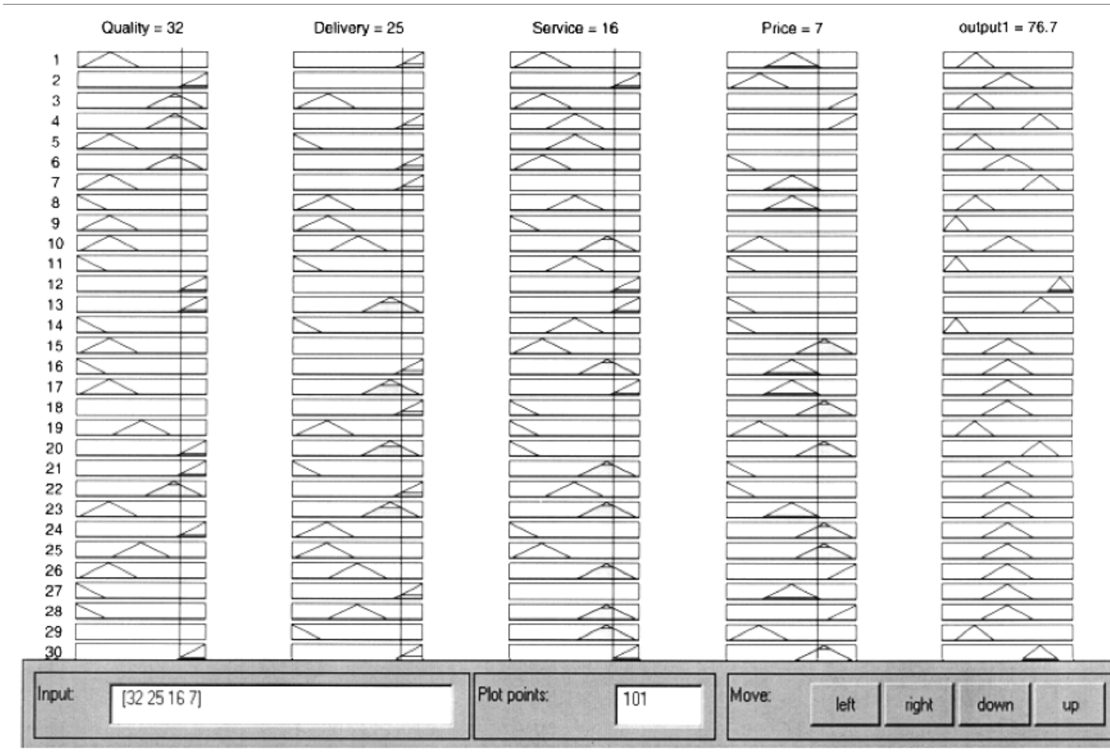
Notes: VL, very low; L, Low; M, medium; H, high; and VH, very high. The corresponding membership values are shown in brackets

this paper is of a process plant. The purchasing manager, on the basis of significance of each criteria and their past data pattern, suggested for inclusion of the four important criteria, namely, QR, DR, SR, and PR for plant-specific supplier performance evaluation model.

Figure 6 shows the rule viewer of the FIS for the linguistic descriptions and the corresponding membership values for one supplier (S_1) corresponding to the attributes selected. In this figure, a set of rules is shown for the supplier performance evaluation. The input attributes for one supplier, the corresponding output score are presented. The fuzzy set activated for this supplier are high for QR, high and very high for DR, high for SR, and high for PR. Two fuzzy rules are fired based on the fuzzy input variables for the suppliers, and the supplier performance score is computed using FIS. Similarly, the performance scores for other suppliers are computed using FIS, and shown in Table IV.

Figure 7 shows one of the output surfaces of the FIS (the actual output surface is a five-dimensional hyperspace). Two input variables, namely SR and PR, have a fixed value of 17 and 7, respectively. The values of two other input variables, namely DR and QR, vary (0 to 30), and (0 to 40), respectively.

Figure 6 An example of the output of the FIS when assessing the supplier performance

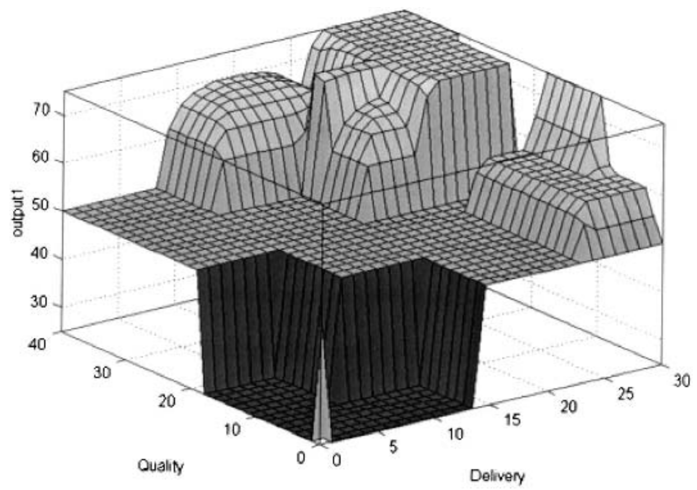


Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 723–734

Table IV Suppliers performance score

Suppliers	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
Suppliers performance score	76.7	80.6	75	50	76.9	68	79.5	75	66.3	75

Figure 7 Output surface of the FIS for the case example



As shown in Figure 7, it may be concluded that as the values of DR and QR increase, the performance score of a supplier increases. Once the knowledge base is prepared and stored in the FIS in the form of rule base, it become easier to forecast the supplier performance score for any combination of suppliers' input attributes.

8. Conclusions

Two most important conclusions pertaining to the methodology of suppliers' performance are as follows:

(1) according to the nature and type of the priorities associated with the products and their suppliers' attributes, the evolution of fuzzy rules are possible using GAs; and
(2) it is quite possible that the rule base does not possess the required rules that are essential to the successful run of the FIS. Under such condition, it is recommended that the length of the chromosome must be large enough to evolve more number of fuzzy rules in the rule base.

For the clarity of presentation and simple illustration of the complex methodology, only a four-attribute case has been considered in this paper. Fairly large problems can also be undertaken and the proposed methodology may offer consistent performance in these cases too. In the present study, a triangular fuzzy membership functions are adopted owing to their simplicity. However, to address the problem in a more realistic way, this restriction may be relaxed, and different membership functions corresponding to each linguistic description can be associated, and the proposed methodology can be implemented in a given situation.

References

Abey, S. and Lan, M.S. (1995), "A method for fuzzy rule extraction directly from the numerical data and its application to pattern classification", *IEEE Trans. on Fuzzy Systems*, Vol. 3, pp. 18-28.

Davis, L. (1991), *Handbook of Genetic Algorithm*, Van Nostrand, Reinhold, New York, NY.

Dickson, G. (1966), "An analysis of vendor selection systems and decisions", *Journal of Purchasing*, Vol. 2, pp. 28-41.

Ellram, L.M. (1995), "Total cost of ownership: an analysis approach for purchasing", *International Journal of Physical Distribution & Logistics Management*, Vol. 25 No. 8, pp. 4-23.

Ghodsypour, S.H. and O'brien, C. (1998), "A decision support system for supplier selection using an integrated analytical hierarchy process and linear programming", *International Journal of Production Economics*, Vol. 56, pp. 199-212.

Goldberg, D.E. (1989), *Genetic Algorithm in Search, Optimization and Machine Learning*, Addision Wesley, Reading, MA.

Jeong, C.S. and Lee, Y.H. (2002), "A multi-criteria supplier selection (MCSS) model for supply chain management", *VISION: The Journal of Business Perspective*, pp. 51-60.

Kanan, V.R., Tan, K.C. and Nevada, L.V. (2002), "Supplier selection and assessment: their impact on business performance", *The Journal of Supply Chain Management*, pp. 11-21.

Lambert, D.M. and Cooper, M.C. (2000), "Issues in supply chain management", *Industrial Marketing Management*, Vol. 29, pp. 65-83.

Lee, E., Ha, S. and Kim, S. (2001), "Supplier selection and management system considering relationships in supply chain management", *IEEE Transactions on Engineering Management*, Vol. 48 No. 3, pp. 307-18.

Lin, C. and Lee, C.S.G. (1996), *Neural Fuzzy Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Li, C.C., Fun, Y.P. and Hung, J.S. (1997), "A new measure for Supplier performance evaluation", *IIE Transactions*, Vol. 29, pp. 753-8.

Mandal, A. and Deshmukh, S.G. (1994), "Vendor selection using interpretative structural modeling (ISM)", *International Journal of Operations & Production Management*, Vol. 14 No. 6, pp. 52-9.

Muralidharan, C., Anantharaman, N. and Deshmukh, S.G. (2002), "A multi-criteria group decisionmaking model for

supplier rating", *The Journal of Supply Chain Management*, pp. 22-33.

Narasimhan, R. (1983), "An analytical approach to supplier selection", *Journal of Purchasing and Materials Management*, Vol. 19 No. 4, pp. 27-32.

Narasimhan, R., Talluri, S. and Mendez, D. (2001), "Supplier evaluation and rationalization via data envelopment analysis: an empirical examination", *The Journal of Supply Chain Management*, pp. 28-36.

Patton, W.W. (1996), "Use of human judgment models in industrial buyer's vendor selection decisions", *Industrial Marketing Management*, Vol. 25, pp. 135-49.

Petroni, A. and Braglia, M. (2000), "Vendor selection using principal component analysis", *The Journal of Supply Chain Management*, Spring, pp. 63-9.

Ross, T.J. (1995), *Fuzzy Logic with Engineering Applications*, Prentice-Hall, London.

Saaty, T.L. (1980), *The Analytical Hierarchy Process*, McGraw-Hill, London.

Siying, W., Jinlong, Z. and Zhicheng, L. (1997), "A supplier-selection system using neural networks", paper presented at the IEEE International Conference on Intelligent Processing System, New York, NY, pp. 468-71.

Soukup, W.R. (1997), "Supplier selection strategies", *Journal of Purchasing and Materials Management*, Vol. 23 No. 2, pp. 7-12.

Stevens, G.C. (1989), "Integrating the supply chain", *International Journal of Physical Distribution and Materials Management*, Vol. 19 No. 8, pp. 3-8.

Tam, M.C.Y. and Tummala, V.M.R. (2001), "An application of AHP in vendor selection of a telecommunications system", *Omega*, Vol. 29, pp. 171-82.

Timmerman, E. (1986), "An approach to supplier performance evaluation", *Journal of Purchasing and Materials Management*, Vol. 22, pp. 2-8.

Tiwari, M.K. and Roy, D. (2002), "Application of an evolutionary fuzzy system for the estimation of workforce deployment and cross-training in an assembly environment", *International Journal of Production Research*, Vol. 40 No. 18, pp. 4651-74.

Verma, R. and Pullman, M.E. (1998), "An analysis of supplier selection process", *Omega, International Journal of Management Science*, Vol. 26, pp. 739-50.

Wang, C.H., Hong, T.P. and Tseng, S.S. (1998), "Integrating fuzzy knowledge by genetic algorithms", *IEEE Trans. on Evolutionary Computation*, Vol. 2 No. 4, pp. 138-49.

Weber, C.A., Current, J.R. and Benton, W.C. (1991), "Vendor selection criteria and methods", *European Journal of Operations Research*, Vol. 68, pp. 173-84.

Willis, T.H., Huston, C.R. and Pohlkamp, F. (1993), "Evaluation measure of just-in-time supplier performance", *Journal of Production and Inventory management*, 2nd Quarter, pp. 1-6.

Yuan, Y. and Zhuang, H. (1996), "A genetic algorithm for generating fuzzy classification rules", *Fuzzy Sets and Systems*, Vol. 84 No. 1, pp. 1-19.

Zadeh, L.A. (1978), "Fuzzy sets as a basis for a theory of possibility", *Fuzzy Sets and Systems*, Vol. 1, pp. 3-28.

Appendix. Procedure for determining expected output value (e_i)

The expected output value (e_i) is determined by putting conditions based on analysis of the data collected on input and output variables including their interrelationships for the plant under consideration.

The expected output value is determined by employing the following procedure:

All the five fuzzy sets of the input and output variables (Figure 2) are assigned an integer value in the range 1 to 5, e.g. 1 = Very Low (VL); 2 = Low (L); 3 = Medium (M); 4 = High (H); and 5 = Very High (VH).

The abbreviations for input and output variables

$$\begin{aligned}
x_1 &= \text{input variable 1, i.e. Quality rating (QR)},\\
x_2 &= \text{input variable 2, i.e. Delivery rating (DR)},\\
x_3 &= \text{input variable 3, i.e. Service rating (SR)},\\
x_4 &= \text{input variable 4, i.e. Price rating (PR)},\\
y_1 &= \text{expected output value } (e_i),\ \text{i.e. supplier}\\
&\quad\ \text{performance score.}
\end{aligned}$$

To get an expected output value, the antecedent part of the IF … THEN rules must satisfy at least one condition as mentioned below.

Condition I

IF [(x_1 is 1 OR x_1 is 2) AND (x_2 is 1 OR x_2 is 2) AND (x_3 is 2 OR x_3 is 3) AND (x_4 is 2 OR x_4 is 3 OR x_4 is 4)] THEN (y_1 is 1).

ELSE

Condition II

IF [(x_1 is 1 OR x_1 is 2) AND (x_2 is 1 OR x_2 is 2) AND (x_3 is 4 OR x_3 is 5) AND (x_4 is 4 OR x_4 is 5)] THEN (y_1 is 2).

ELSE

Condition III

IF [(x_1 is 1 OR x_1 is 2) AND (x_2 is 3) AND (x_3 is 3) AND (x_4 is 3)] THEN (y_1 is 3).

ELSE

Condition IV

IF [(x_1 is 3 OR x_1 is 4) AND (x_2 is 3 OR x_2 is 4 OR x_2 is 5) AND (x_3 is 1 OR x_3 is 2) AND (x_4 is 4 OR x_4 is 5)] THEN (y_1 is 4).

ELSE

Condition V

IF [(x_1 is 4 OR x_1 is 5) AND (x_2 is 4 OR x_2 is 5) AND (x_3 is 2 OR x_3 is 3 OR x_3 is 4) AND (x_4 is 4 OR x_4 is 5)] THEN (y_1 is 5).

Evaluation of the supplier performance using an evolutionary fuzzy-based approach

Vipul Jain
M.K. Tiwari and
F.T.S. Chan

The authors

Vipul Jain and **M.K. Tiwari** are based in the Department of Manufacturing Engineering, National Institute of Foundry and Forge Technology (NIFFT), Ranchi, India.
F.T.S. Chan is based in the Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, People's Republic of China.

Keywords

Supply chain management, Supplier evaluation

Abstract

Different entities in a supply chain network operate in a highly interdependent environment when it comes to improving performance of the network in terms of objectives such as delivery performance, quality assurance and cost minimization, etc. In this research, an attempt has been made to evaluate the supplier performance by adopting evolutionary fuzzy system owing to the linguistic nature of the attributes associated with the suppliers and manufacturing units. The proposed methodology offers consistently good performance when applied to a variety of standard problems related to evaluation of supplier's performance available in the literatures.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

1. Introduction and related research

A supply chain can be defined as a network of autonomous or semi-autonomous business entities involved, through upstream and downstream links, in different processes and activities that yield physical goods or deliver services to the customer (Lee and Billington, 1993; Swaminathan *et al.*, 1997). Figure 1 shows a generic supply chain network (SCN) where nodes represent business and production entities connected by material flow links. Operation of different entities in a supply chain is restricted by different sets of constraints and objectives. Performance improvement of the supply chain considering the main objectives of on time delivery, quality assurance and cost minimization are highly interdependent. This affects the performance of any entity in a supply chain, which depends on the performance of others, and their willingness and ability to coordinate activities within a supply chain. Several researchers in the recent past discussed these important issues and common processes, occurring in different types of supply chains to develop a realistic framework (Swaminathan *et al.*, 1997; Sabel *et al.*, 1989). Variations in supply chains are observed in terms of stages of decision-making, heterogeneity in supply chain and relationship with suppliers. For instance, in the supply chain dealing with the manufacture of computers, it was observed that decision-making process was centralized to a large extent, more preference were accorded to few suppliers while others were controlled by the manufacturers themselves.

One of the important issues that has been studied is the performance of SCNs. Several empirical studies have reported observations of the global and local performance of SCNs. Cash and Konsynski (1985), Swaminathan *et al.* (1995) mentioned in their study that sometime, taking a global perspective may have unfavorable effects on some of the entities of the supply chains (Swaminathan *et al.*, 1997). Albino *et al.* (1998) have applied the concept of vulnerability to production systems in order to provide a little insight into the effect of uncertainty and variability on systems performance.

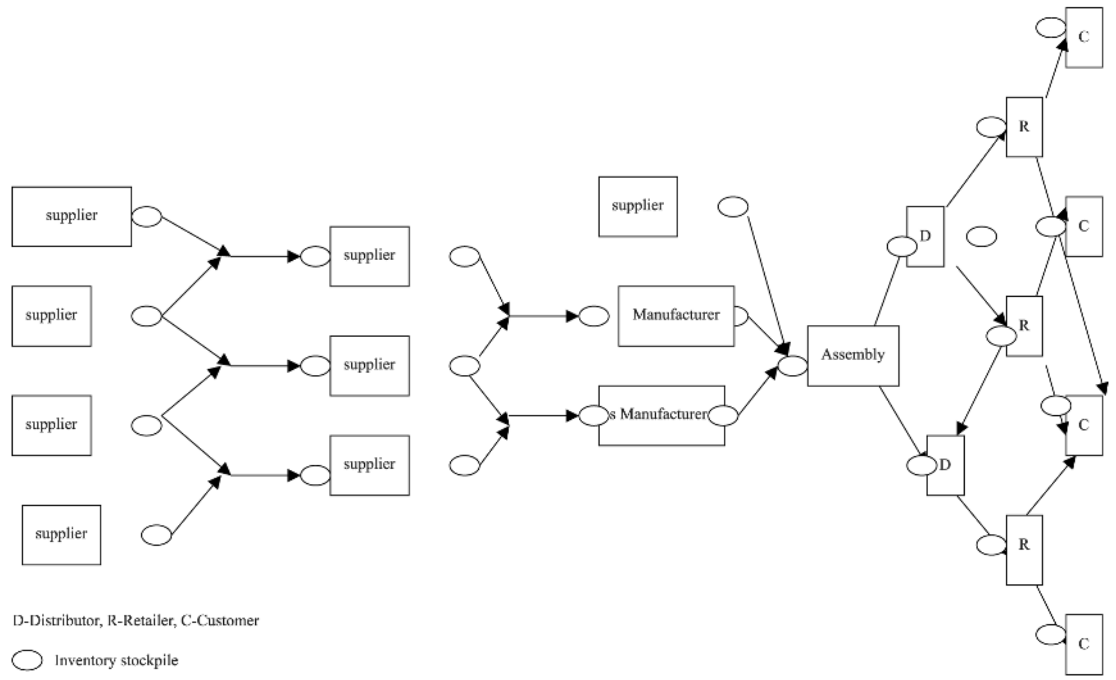
In order to ensure the uninterrupted supply of items, it has been observed that more than one supplier or vendor is normally available for each item. Periodic evaluation of supplier quality is carried out to ensure the meeting of relevant quality standards for all incoming items. Price alone should not be the yardstick for assessing the supplier performance, rather the "cost of

Received: 29 March 2003
Accepted: 20 March 2004

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 735–744

· ISSN 1741-038X
DOI 10.1108/17410380410565320

Figure 1 A generic structure of a SCN



ownership of materials" appears to be more appropriate (Albino *et al.*, 1998). It is worth mentioning here that in some of the recent studies, the essential requirements advocated for supplier selection are: quality, cost, delivery, flexibility and response (Li *et al.*, 1997; Talluri and Sarkis, 2002). In recent years, several proposals for evaluating the performance of suppliers have been reported in the literatures, including notable among them are Categorical method, Weighted Point method, and Cost-Ratio method (Dobler *et al.*, 1990; Timmerman, 1986). Soukup (1997) suggested supplier selection strategies using the Weighted Point method. Narasimhan (1983) proposed an analytic hierarchic process (AHP) based methodology for the supplier selection. The above-mentioned methodologies each have some advantages under specific conditions, but none offers a generic methodology, which can combine several criteria or attributes into a single measure of supplier performance. Li *et al.* (1997) proposed a new supplier performance measure employing the concept of dimensional analysis. They suggested a standardized unitless rating (SUR) combining the weighted average of qualitative and quantitative scores associated with each supplier. Selection criteria in supplier selection play an important role in identifying supplier performance (Min, 1993; Rebstock and Kaula, 1996; Vokurka *et al.*, 1996; Barbarosoglu and Tazgac, 1997; Krause and Ellram, 1997; Ghodsypour and O'Brien, 1998; Verma and Pullman, 1998; Motwani *et al.*, 1999; Dowlatshahi, 2000; Shin *et al.*, 2000; Humphreys *et al.*, 2001; Liu *et al.*, 2000). Chan (2003) proposed a model named interactive selection model (ISM) with AHP to handle the supplier selection process (SSP) systematically and quantitatively. Comprehensive reviews of methods supporting supplier selection have been addressed by Boer *et al.* (2001). Nassembeni and Battain (2003) present a fuzzy expert system prototype able to manage the evaluation process and to offer a reliable measurement of the contribution of the suppliers in new product development (NPD).

In this research, a realistic approach based on the concept of an evolutionary fuzzy system is developed to assess the performance of suppliers. Owing to their diverse and linguistic nature, supplier attributes usually need to be categorized prior to further analysis. Cross functional teams supposed to rate the supplier's attribute in linguistic descriptions viz. very low, low, medium, high and very high, respectively. Linguistic assessment of suppliers is to be carried out on the following criteria such as quality, response to special orders, delivery performance, ease of ordering, stocking programs. To address the suppler selection problem, technical as well as financial implications have to be considered in order to ensure the effective mapping of the functional attributes on to the relevant product attributes.

Because of the imprecise nature of linguistic attributes, inconsistencies in the judgement are bound to crop up regarding the grading of supplier

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 735–744

performance. Supplier ranking is also carried out by a pair-wise comparison-based method such as AHP and Conjoint analysis (Saaty, 1990; Green *et al.*, 1972; Green, 1978), but the results are prone to judgmental error. To deal with these inconsistencies, a fuzzy method is suggested to convert the suppliers' linguistic attributes into fuzzy numbers and relative supplier performance is assessed using fuzzy arithmetic.

In this research, an evolutionary fuzzy system-based approach is suggested to take care of the above-mentioned complications related to the qualitative assessments of the supplier.
The proposed evolutionary fuzzy system maintains a population of fuzzy rule sets with their membership functions and uses a genetic algorithm (GA) to evolve the resulting feasible fuzzy rule base. One of the key considerations in designing the proposed evolutionary fuzzy system is the generation of the fuzzy rules as well as the membership functions for each fuzzy set. With few inputs, the cross-functional terms are used to generate the fuzzy rules related to several performance attributes of a supplier. With an increasing number of variables, the numbers of fuzzy rules increase exponentially, which makes it difficult for the cross-functional terms to define a complete rule base for good support decision system. Therefore, it is essential to develop an automated way to design a fuzzy system having the capability to evolve the optimal set of fuzzy rules using a GA. In the recent past several researchers such as Wang *et al.* (1998), Carse *et al.* (1996), Lee and Takagi (1993), Thrift (1991), Wang *et al.* (1997), Yuan and Zhuang (1996), Borea and Wang (2003) have adopted evolutionary fuzzy systems in the areas of fuzzy data classification, prediction and control. The proposed evolutionary fuzzy algorithm is applied to assess supplier performance for a hypothetical firm.

The rest of this paper is organized as follows. An overview of fuzzy expert systems is given in Section 2 while Section 3 describes the application of the proposed evolutionary fuzzy system for supplier performance evaluation. Computational experiences on the implementation of the proposed approach along with a case study are presented in Section 4. The conclusions and scope for further study are reported in Section 5.

2. Fuzzy expert system

In many real world applications, fuzzy systems that make use of the linguistic rules are well suited to describe the behavior of complex systems problems, which are difficult to model mathematically. Fuzzy theorists use fuzzy sets to represent the nonstatistical, uncertainty and approximate reasoning and apply to real life data. Thus, Zadeh (1965, 1978) extended the bivalent indicator function I_A of the non fuzzy subset A of X, such that:

$$I_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{Otherwise} \end{cases}$$

to a multi valued indicator or membership function in which the membership function maps each element x in X to a real number in the interval [0,1]. The function value $m_A(x)$ then represents the grade of membership of x in A. The larger $m_A(x)$, stronger the grade of membership for x in A. The membership function can typically take linear or nonlinear forms including left-triangle, right-triangle, triangle, Gaussian and sigmoid functions. Each membership function is determined by two values: the start point x_1, and the end point x_2. Each fuzzy variable can have any number of fuzzy sets and each set can be either linear or nonlinear form of membership functions (Ross, 1997; Zimmerman, 1991).

In an n-input-single-output fuzzy system, the fuzzy rules have the following general format:

$$R_{\mathrm{j}}: \text{IF } X_1 \text{ is } Y_{1,j} \text{ And } X_2 \text{ is } Y_{2,j}$$
$$\text{And}\ldots\text{And } X_n \text{ is } Y_{n,j} \text{ Then } Y \text{ is } Z_j$$

where the variables $X_i (i = 1, \ldots, n)$ appearing in the antecedent parts of the fuzzy rules R_j are called the input linguistic variables, the variable Y in the consequent part of the fuzzy rule R_j is called the output linguistic variable, the fuzzy sets $Y_{i,j}$ are called the input fuzzy sets of the input linguistic variable X_i of the fuzzy rule R_j, and the fuzzy set Z_j is called the output fuzzy set of the output linguistic variable Y of the fuzzy rule R_j.

A fuzzy expert system is defined if and only if the rule sets and membership functions associated with its fuzzy sets are defined. All the fuzzy rules in a fuzzy system are fired in parallel mode. The working of a fuzzy expert system can be described as follows:

(1) evaluate the values of fuzzy membership by energizing the inputs;
(2) obtain the fuzzy rules, which are fired in the rule set;
(3) adopting the AND operator, group the values of membership for each energized rule;
(4) use a search rule supported by the min-max compositional rule to obtain the appropriate output fuzzy membership value;
(5) determine the value of each output variable by defuzzification uses the weighted average method; and
(6) take decisions according to the output values.

The process of making a crisp quantity fuzzy is termed as fuzzification. Certain quantities that we consider crisp and deterministic are actually nondeterministic and carry considerable uncertainty (Zadeh, 1965). For instance, measuring instruments generate crisp data, but these data are subjected to experimental error. Thus, the form of uncertainty arises because of imprecision, ambiguity or vagueness, the variable, therefore is then fuzzy and can be represented by a membership function. Each input variable activates one or more fuzzy sets according to the definitions of the fuzzy membership functions. After the fuzzification of the variables, the rules with at least one activated antecedent set are said to be fired by the inputs. Then the AND ($\wedge$) operator is employed to combine the membership values for each fired rule to generate the membership values for the fuzzy sets of the output variables in the consequent part of the rule.

Owing to the partial overlapping of the fuzzy sets corresponding to the input variables, several rules may be fired in a parallel mode. Thus, for some fuzzy sets of the output variables there may be different membership values obtained from different fired rules. The most common procedure adopted to combine these values is by employing the OR ($\vee$) operator, that takes the maximum value as the membership value of that fuzzy set. The output of a fuzzy process needs to be a single scalar quantity as opposed to the input quantity in a fuzzy set. Defuzzification is the conversion of a fuzzy data to a precise data as opposed to the process of fuzzification, i.e. conversion of a precise data to a fuzzy data. Popular defuzzification approaches includes Max-membership principle, centroid method, weighted average method, mean-max membership, center of sums, center of largest area, and first (or last) of maxima (Zadeh, 1978). In this paper, weighted average method is adopted to defuzzify the fuzzy output data as this methodology is only valid for symmetric output membership function. It is given by algebraic expression:

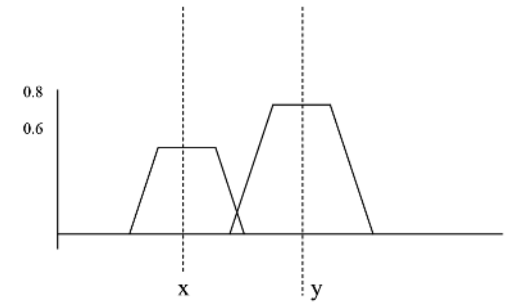
$$Z^{\star} = \frac{\Sigma \mu_c(\bar{z}) \cdot \bar{z}}{\Sigma \mu_c(\bar{z})} \tag{1}$$

The weighted average method is formed by weighing each membership function in the output by its respective maximum membership value. For instance, the two functions shown in Figure 2 would result in the following general form for the defuzzified value:

$$Z^{\star} = x(0.6) + y(0.8)/(0.6 + 0.8) \tag{2}$$

As this approach of defuzzification is restricted to symmetrical membership functions, the values x and y are the means of their respective shapes.

Figure 2 Illustration of weighted average method for defuzzification



Then, based on the crisp output data, practical decisions can be made to solve the problem. In this paper based on the crisp output data, the supplier's performances are graded.

3. Evolutionary fuzzy expert systems

It has been observed that in the majority of existing applications, the fuzzy rules are generated by experts and decision-makers have to deal with only a few inputs. The possible number of fuzzy rules for a given system grows exponentially when the number of input variables increases. For example, in the evaluation of a supplier performance with ten attributes where each attribute consists of five linguistic descriptions (very low, low, medium, high, very high) then the possible number of fuzzy rules are 5^{10}. It is too difficult, if not impossible for an expert to define a complete rule set for assessing the supplier performance. There are several methods such as clustering algorithms, pattern classification methods, etc. to practice an automated way to design fuzzy system (Ross, 1997; Zimmerman, 1991; Abey and Lan, 1995; Bezdek, 1992). In case of large number of input variables in a complex system, these systems fail as they tend to extract rules, which become independent of the membership functions and leads to the degradation of the solution.

In several cases, performance is found to be improved by tuning the membership functions and selecting suitable fuzzification and defuzzification methods. In this paper, an evolutionary fuzzy system has been employed in which the fuzzy rule set, and number of rules inside the rule set are generated using a powerful and intelligent search algorithm known as a GA to assess the supplier performance. GAs have recently found its growing application in solving several types of linear and nonlinear optimization problems. GA is a mature tool and interested readers are advised to refer to Goldberg (1989), Davis (1991), and Deb (1996). This fact motivated the researchers to use this intelligent optimization tool for the generation of a

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 735–744

set of fuzzy rules required to design the fuzzy rule base. The various constituents of the proposed evolutionary fuzzy system are described as follows.

3.1 Representation

The first important consideration while designing a fuzzy expert system using GA is the representation strategy adopted to encode the fuzzy system into the chromosome. A fuzzy system is well defined only when the fuzzy rule base and the membership functions associated with each fuzzy set of a variable are specified. Thus, it is practically realized to completely represent a fuzzy expert system, each chromosome must encode all the requisite information about the rule sets and the membership functions.

For example, we consider a fuzzy system with five input variables and one output variable with each variable (input/output) having five fuzzy sets representing the linguistic descriptions: very low, low medium, high and very high. The fuzzy sets corresponding to each input/output can be represented by the integers 1-5. The use of integer 0 is to represent the absence of a term. In this way, a fuzzy rule can be represented by six integers. Consider an example rule for which input 1 is medium, input 2 is very high, input 3 is low and input 5 is high, then the output is very low and the rule can be encoded as 3 5 2 0 4 1. If a rule base includes 15 such rules, then an integer string of length 90 can represent the rule set completely.

In this paper, a total of four variables with each variable having five fuzzy set is considered to evaluate the suppliers' performance. The fuzzy set membership functions: left-triangle, triangle, triangle, triangle, right-triangle functions corresponds to the fuzzy sets of input variables: very low, low, medium, high and very high, respectively. The start and end point of the membership functions are fixed as per the need of the various problems. For the output variable all the fuzzy sets are represented by triangular membership functions. In the underlying example for evaluating the supplier performance, the input variables considered are part rejection rate, delivery performance, residual stress and surface finish of the product.

The fuzzy rules in the rule base and the number of such fuzzy rules that are associated with the problem are to be evolved using a GA. In order to reduce the search space, it is advocated that the maximum number of rules concerning any problem is fixed in advance. After performing exhaustive trial and error experimentation, the maximum number of acceptable rules undertaken in this study is limited to 40. Then the total length of the chromosome representing the system is:

$$1 + 5^{*}(40) = 201$$

and the system can be represented as:

$$S_1 S_2 S_3 S_4 S_5 S_6 \ldots S_{57} S_{58} S_{59} \ldots S_{140} S_{141} \ldots$$

$$S_{199} S_{200} S_{201},$$

where S_1 represents the number of rules varying between 1 and 40, S_2, $S_3, \ldots, S_6$ encodes the first fuzzy rule in the rule set and S_{197}, $S_{198} \ldots S_{201}$ represents the last fuzzy rule in the rule set. S_1 denotes the number of possible rules that are used to design the rule base. However, it is observed that each rule may not be feasible. A rule with a zero antecedent or consequent part is an infeasible rule and should be excluded from the fuzzy rule base. In order to ensure that the chromosome contains no infeasible rules, the fitness value corresponding to the chromosome is assigned to a very small floating number [0,1], so that these chromosomes do not pass over to the next generation.

3.2 Fitness function

Another important consideration following the representation of the chromosome is the selection of the fitness function. While the genotype representation encodes the rule base into an integer string, the fitness function evaluates the performance of the rule base. For the evaluation of supplier performance using GAs, a good fitness measurement for a system is quite essential. The fitness measurement function varies with the problem environment. For prediction and estimation problems, the mean-square error or absolute difference error related function is most commonly used.

$$E = 1/N \;\; \Sigma(o_i - e_i)^2 \tag{3}$$

$$E = 1/N \;\; \Sigma|o_i - e_i| \tag{4}$$

where N is the number of training data, o_i and e_i are the ith obtained and expected outputs, respectively.

In this paper, the mean-square error function is determined to evaluate the fitness of the chromosomes.

$$E = 1/N \;\; \Sigma(o_i - e_i)^2 \tag{5}$$

where N is the number of evolved fuzzy rules, e_i is the expected outputs obtained by assigning priorities to the input variable (discussed in Section 4)

$$\text{Fitness value} = \frac{1}{1+E} \tag{6}$$

Chromosomes with higher fitness value are carried to the next generation.

3.3 Crossover operator

Crossover is a process by which two parent strings recombine to produce two new offspring strings. An overall probability is assigned to the crossover process. Given two parent chromosomes, the algorithm invokes crossover only if a randomly generated number in the range of 0-1 is greater than crossover rate (it is also known as crossover probability), otherwise the strings remain unaltered. This probability is often in the range of 0.65-0.80. Two-point crossover probability is used in this research with a probability in the range of 0.75-0.90.

3.4 Mutation operator

After crossover, normally strings are subjected to mutation. Mutation randomly alters few composition of a string to produce a new offspring instead of recombining two strings. In traditional GA mutation of a bit involves flipping it or changing a "0" to "1" or vice versa. It is found that the chromosome representing the fuzzy expert system is integer-based instead of binary-based, i.e. each element of the string has an integer range representing the various states of the variable (input/output). The mutation operator used is thus a bit different than that used in binary encoding. Each time an element is chosen to be mutated, it is increased or decreased by replacing it by an integer in the range [1, 5] excluding the present value of the element. The integers of the string are independently mutated, i.e. the mutation of the element does not influence the probability of mutation of another element.

The system flowchart for illustrating the assessment of supplier performance based on evolutionary fuzzy system is shown in Figure 3(a) and (b).

4. Computational experiences

The implementation of the evolutionary fuzzy system for assessing the supplier's performance is written in C++ and compiled using the BC++ compiler. A numerical illustration of automobile company is being taken to describe the working and efficacy of the model. The supplier performance is graded based on the attributes, which were selected from both the supplier and product's point of view. They are, namely: part rejection rate, delivery performance, residual stress, and surface finish. In order to evolve the fuzzy rule base using GAs, a good fitness function is essential. Here, a least mean square function is adopted for fitness measurement, where the expected outputs are determined by prioritizing the attributes. Each feasible fuzzy rule that is evolved in the rule base has the maximum prioritized attribute in the first position, the next prioritized attribute in the second position and like wise. These priorities are analogous to the weights that are being assigned to the attributes and reveal about the relative importance among themselves.

The fuzzy membership functions associated with the fuzzy sets of each input are left-triangle, triangle, triangle, triangle, and right-triangle corresponding to the linguistic descriptions very low, low, medium, high and very high. The ranges and the overlap area of the membership functions are fixed. A triangular fuzzy membership function has been adopted for representing the fuzzy sets of the output variable.

Figure 4 shows the various membership functions for denoting the fuzzy sets of the input/output variable.

Simulations have been carried out to design the fuzzy rule base by varying different GA parameters namely cross over, and mutation probability. The number of generations and the population in the GA run was fixed to 50 and 15, respectively. After performing extensive computations it is found that the optimum and the average fitness values approaches to a maximum value of 0.909091 for a crossover probability of 0.9 and mutation probability of 0.08. The fitness value verses generation graph for three different GA runs is shown in Figure 5. The sets of fuzzy rules evolved using GA with crossover probability 0.9 and mutation probability 0.08 are provided in Table I.

The implementation of the proposed methodology on a test case taken from automobile part manufacturing company is carried out and the related data are given in Table II.

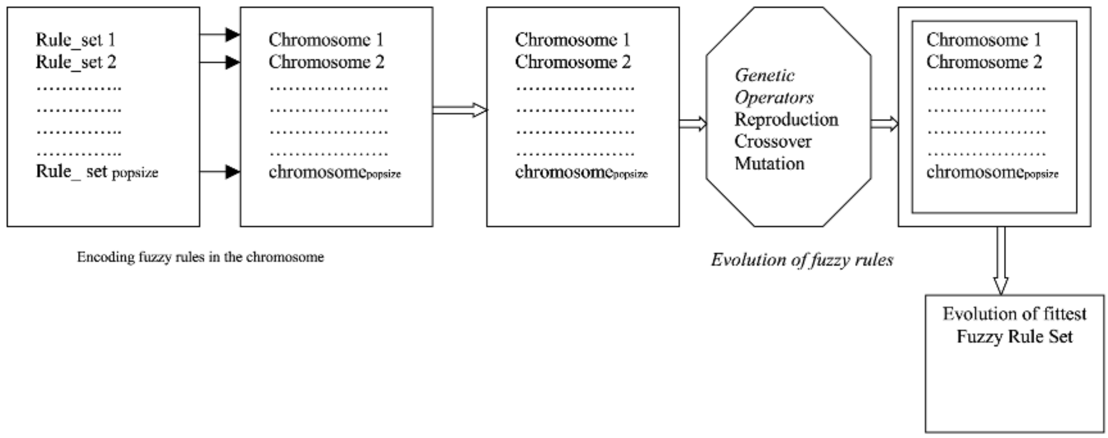
5 Case study

In this study, performance evaluation of five suppliers is carried out against four attributes, combining the characteristics associated with the supplier and product. Various steps of the proposed methodology as described in Figure 3(b) are applied for different suppliers for their performance assessments. Details pertaining to computation of membership function for each supplier along with their attributes are given as shown in Tables III-VII.

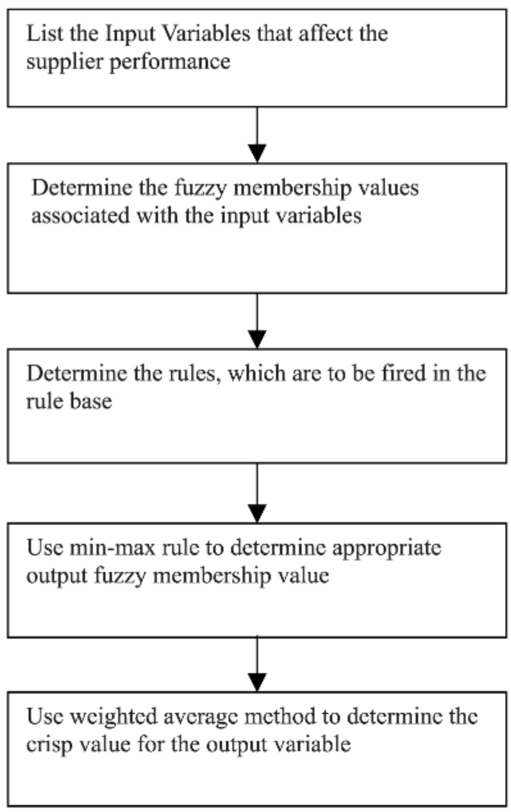
5.1. Concluding remarks and further scope of research

Supplier performance evaluation is one of the important ingredients for the successful

Figure 3



(a) System flowchart for illustrating the evolution of optimum fuzzy rule base



(b) System flow for assessing suppliers's performance based on evolutionary fuzzy system

implementation of the strategies of SCN. Several recent studies with regard to supplier's performance were critically examined. A novel methodology based on the evolutionary fuzzy system is employed to assess the performance of supplier. Efficacy and intricacy of the model is demonstrated with the help of a numerical example. Based on the extensive computational experimentation, values of genetic parameters were fixed to track the optimum set of fuzzy rules to develop foundation of fuzzy expert system for assessing supplier performance. Some of the important observation pertaining to the study is as follows.

(1) According to the nature and type of the priorities associated with the products and their suppliers attributes, the evolution of fuzzy rules are possible using GAs.
(2) It is quite possible that rule base does not process the requisite rules that are essential to the successful run of the expert system. Under such circumstance it is recommended that the

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 735–744

Figure 4 (a,b,c,d,e): The membership function for various supplier performance evaluation attributes

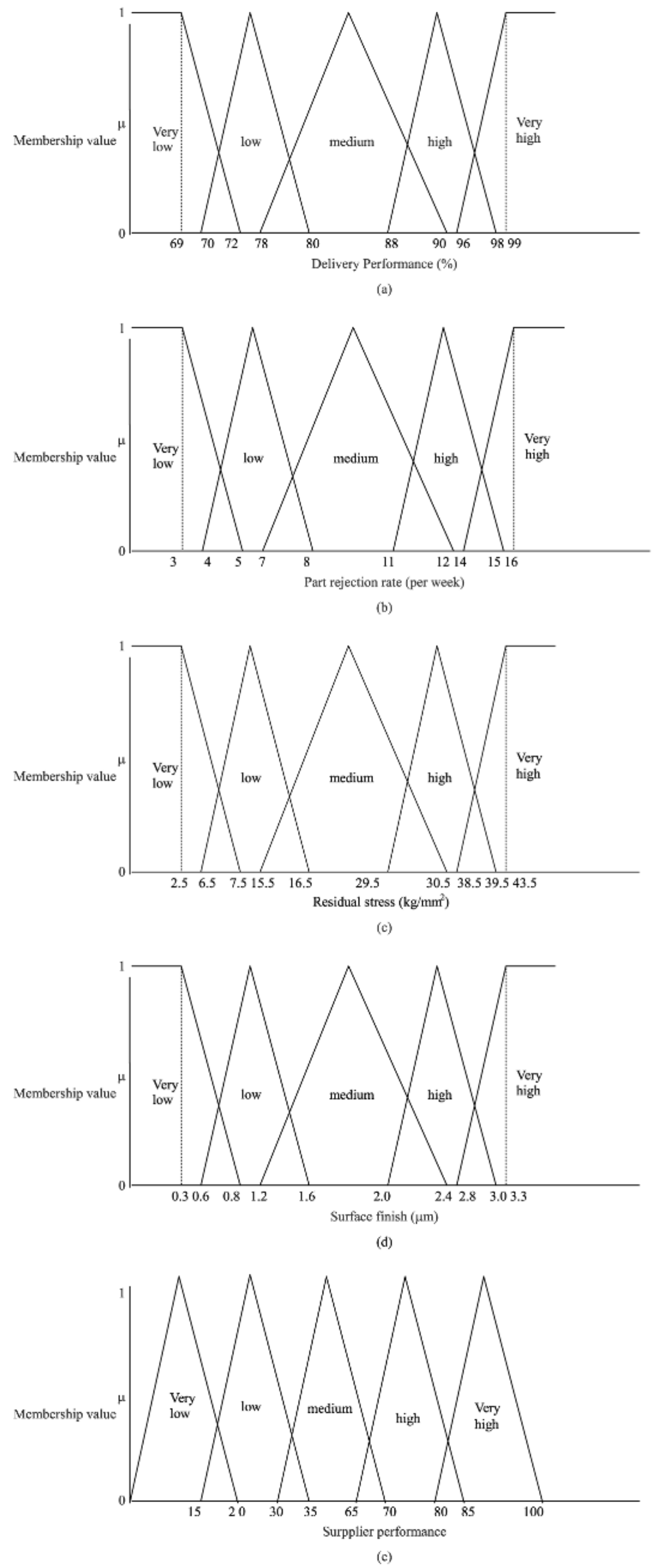


Figure 5 Convergence of GA with different crossover and mutation probabilities

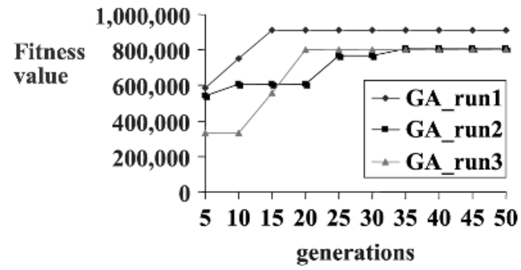


Table I Fuzzy rule base evolved using GA

Rule number	Part rejection rate (PR)	Delivery performance (DP)	Residual stress (RS)	Surface finish (SF)	Supplier performance
1	3	5	3	5	5
2	2	1	1	1	4
3	1	5	2	5	5
4	1	2	2	4	5
5	5	4	2	5	1
6	1	4	3	2	4
7	4	5	4	1	2
8	5	4	1	1	2
9	2	3	2	3	3
10	3	1	5	1	1
11	2	1	3	4	3
12	4	1	3	2	1
13	2	5	4	1	2
14	1	4	4	1	3
15	2	4	4	5	3
16	3	5	3	3	3
17	3	1	1	2	4
18	2	2	2	3	3
19	1	3	4	5	2
20	3	5	4	3	3
21	3	5	4	2	3
22	1	5	1	1	4
23	1	4	4	2	3
24	1	3	1	4	5
25	5	4	1	4	1
26	1	5	2	1	4
27	3	5	3	2	3
28	3	4	3	5	5

Notes: 1 → very low, 2 → low, 3 → medium, 4 → high, and 5 → very high; 28 rules evolved using GA with crossover probability = 0.9 and mutation probability = 0.08

length of the chromosome must be large meaning more number of fuzzy rules in the rule base are ought to be evolved in the GA run.

For the clarity of presentation and simple illustration of the complex methodology, only four attribute case has been considered in this paper. Fairly large problems have also been undertaken by the authors and proposed methodology that

Table II Relationship among suppliers and their attributes

Part rejection rate (Per week)	Delivery performance[a] (percent)	Residual stress (ug/mn42)	Surface finish[b] (m)
4	98	5	0.5
3	86	32	4.5
11	98	3	1.3
4	95	32	0.7
7	78	8	1.9

Notes: [a]Supplier attribute; [b]Product attribute

Table III For supplier 1

Attribute	Crisp data	Activated fuzzy set	Membership value
PR	4	Very low	0.5
DP	98	Very high	0.33
RS	5	Very low	0.5
SF	0.5	Very low	0.4

Notes: Total number of rules fired = 1; The sequence of the rule fired in the evolved fuzzy rule base = 22 (refer Table I); Supplier performance is high with a membership value of 0.33 (As per min-max composition rule); Defuzzified value of performance for supplier 1 = $0.33 \times 70 = 23.1$

Table IV For supplier 2

Attribute	Crisp data	Activated fuzzy set	Membership value
PR	3	Very low	1.0
DP	86	Medium	0.667
RS	32	High	0.5
SF	4.5	Very high	1.0

Notes: Total number of rules fired = 1; The sequence of the rule fired in the evolved fuzzy rule base = 19; Supplier performance is low with a membership value of 0.5; Defuzzified value of performance for supplier 2 = $0.5 \times 25 = 12.5$

Table V For supplier 3

Attribute	Crisp data	Activated fuzzy set	Membership value
PR	4	Medium	0.5
DP	98	Very high	0.33
RS	30	Medium	0.0333
		High	0.1
SF	1.3	Low	0.6
		Medium	0.1667

Notes: Total number of rule fired = 4; the sequence of the rules fired in the evolved fuzzy rule base = 27,16,21,20 (refer table I), *Rule 1*: If ((PR = medium) and (DP = very high) and (RS = medium) and (SF = low)) then supplier performance is high with membership value of 0.0333, *Rule 2*: If ((PR = medium) and (DP = very high) and (RS = medium) and (SF = medium)) then supplier performance is high with membership value of 0.0333, *Rule 3*: If ((PR = medium) and (DP = very high) and (RS = high) and (SF = low)) then supplier performance is medium with membership value of 0.1, *Rule 4*: (If ((PR = medium) and (DP = very high) and (RS = high) and (SF = medium)) then supplier performance is medium with membership value of 0.1, Using weighted average method of defuzzification supplier performance = $(70 \times (0.0333) + 45 \times (0.1))/(0.0333 + 0.1) = 51.25$

Table VI For supplier 4

Attribute	Crisp data	Activated fuzzy set	Membership value
PR	4	Very low	0.5
DP	95	High	0.6
RS	32	High	0.5
SF	0.7	Very low	0.5
		Low	0.5

Notes: Total number of rules fired = 2; the sequence of the rules fired in the evolved fuzzy rule base = 14,23, *Rule 1*: If (PR = very low) and (DP = high) and (RS = high) and (SF = very low) then supplier performance is medium with a membership value of 0.5, *Rule 2*: If (PR = very low) and (DP = high) and (RS = high) and (SF = low) then supplier performance is medium with a membership value of 0.5, Supplier performance = $0.45 \times 0.5 = 22.5$

Table VII For supplier 5

Attribute	Crisp data	Activated fuzzy set	Membership value
PR	7	Low	0.5
DP	78	Low	0.4
RS	8	Low	0.3
SF	1.9	Medium	0.833

Notes: Total number of rules fired = 1. The sequence of the rule fired in the evolved fuzzy rule base = 18. Supplier performance is medium with a membership value of 0.3. Supplier performance = $45 \times 0.3 = 13.5$. $\therefore$ The order of performance of the suppliers is supplier 3, supplier 1, supplier 4, supplier 5, supplier 2

offers consistent performance is observed in these cases too. This research can be further extended using other types of crossover and mutation operators. In the present study, we have restricted to left-triangles, right-triangle and triangular membership functions owing to their simplicity. However to address the problem in a more pragmatic way, this restriction can be relaxed that means different membership functions corresponding to each linguistic description can be associated, thereafter the implementation of the proposed methodology can be followed.

Hopefully, the idea suggested in this paper will be of some interest to the supply chain management professions to evaluate the performance of suppliers in medium and large industries.

References

Abey, S. and Lan, M.S. (1995), "A method for fuzzy rule extraction directly from the numerical data and its application to pattern classification", *IEEE Trans. on Fuzzy Systems*, Vol. 3, pp. 18-28.

Albino, V., Garavelli, C. and Okogbaa, O.G. (1998), "Vulnerability of production systems with multi-supplier network: a case study", *International Journal of Production Research*, Vol. 36 No. 11, pp. 3055-66.

Barbarosoglu, G. and Tazgac, T. (1997), "An application of the analytical hierarchy process to the supplier selection problem", *Productions and Inventory Management Journal*, First Quarter, pp. 14-21.

Bezdek, J.C. (1992), "On the relationship between neural networks, pattern recognition and intelligence", *Int. J. of Approximate Reasoning*, Vol. 6 No. 2, pp. 85-107.

Boer, L., Labro, E. and Morlacchi, P. (2001), "A review of methods supporting supplier selection", *European Journal of Purchasing and Supply Management*, Vol. 7, pp. 75-89.

Borea, M.D. and Wang, B. (2003), "A Identifying environmental improvement options by combining life cycle assessment and fuzzy set theory", *International Journal of Production Research*, Vol. 41 No. 3, pp. 593-610.

Carse, B., Fogarty, T.C. and Munro, A. (1996), "Evolving fuzzy rule based controllers using genetic algorithms", *Fuzzy Sets and Systems*, Vol. 80, pp. 273-93.

Cash, J.I. and Konsynski, B.R. (1985), "IS redraws competitive boundaries", *Harvard Business Review*, Vol. 63 No. 2, pp. 134-42.

Chan, F.T.S. (2003), "Interactive selection model for supplier selection process: an analytical hierarchy process approach", *International Journal of Production Research*, Vol. 41 No. 15, pp. 3549-79.

Davis, L. (1991), *Handbook of Genetic Algorithm*, Van Nostrand, Reinhold, New York, NY.

Deb, K. (1996), *Optimization for Engineering Design. Algorithms and Examples*, Prentice Hall, New Delhi.

Dobler, D.W., Lee, L. Jr and Burt, D.N. (1990), *Purchasing and Materials Management: Text and Cases*, 5th ed., McGraw-Hill, New York, NY.

Dowlatshahi, S. (2000), "Designer-buyer-supplier-interface: theory versus practice", *International Journal of Production Economics*, Vol. 63, pp. 111-30.

Ghodsypour, S.H. and O'Brien, C. (1998), "A decision support system for supplier selection using an Integrated analytic hierarchy process and linear programming", *International Journal of Production Economics*, Vol. 56-57, pp. 99-122.

Goldberg, D.E. (1989), *Genetic Algorithm in Search. Optimization and Machine Learning*, Addison Wesley, Reading, MA.

Green, P.E. and Srinivasan, V. (1978), "Conjoint analysis in consumer research: issues and outlook", *Journal of Consumer Research*, Vol. 5, pp. 103-23.

Green, P.E., Carmove, F.J. and Wind, Y. (1972), "Subjective evaluation models and conjoint measurement", *Behavioral Science*, Vol. 17, pp. 288-99.

Humphreys, D.K., Shin, W.K. and Chan, F.T.S. (2001), "Collaborative buyer-supplier relationships in Hongkong manufacturing firms", *Supply Chain Management: An International Journal*, Vol. 6, pp. 152-62.

Krause, D.R. and Ellram, L.M. (1997), "Success factors in supplier development", *International Journal of Physical Distribution & Logistics Management*, Vol. 27, pp. 39-52.

Lee, H.L. and Billington, C. (1993), "Material management in decentralized supply chains", *Journal of the Operation Research*, Vol. 41 No. 5, pp. 835-47.

Lee, M.A. and Takagi, H. (1993), "Dynamic control of genetic algorithms using fuzzy logic techniques", *Proc. Int. Conf. Genetic Algorithms*, Urbana Champaign, IL, July, pp. 76-83.

Li, C.C., Fun, Y.P. and Hung, J.S. (1997), "A new measure for supplier performance evaluation", *IIE Transactions*, Vol. 29, pp. 753-8.

Liu, F., Ding, F.Y. and Lall, V. (2000), "Using data envelopment analysis to compare suppliers for supplier selection and performance improvement", *Supply Chain Management*, Vol. 5, pp. 143-50.

Min, H. (1993), "International supplier selection: a multi-attribute utility approach", *International Journal of Physical Distribution & Logistics Management*, Vol. 24, pp. 24-33.

Motwani, J., Youssef, M., Kathawala, Y. and Futch, E. (1999), "Supplier selection in developing countries: a model development", *Integrated Manufacturing Systems*, Vol. 10, pp. 154-61.

Narasimhan, R. (1983), "An analytical approach to supplier selection", *Journal of Purchasing and Materials Management*, Vol. 19 No. 4, pp. 27-32.

Nassembeni, G. and Battain, F. (2003), "Evaluation of supplier contribution to product development fuzzy and neuro fuzzy based approaches", *International Journal of Production Research*, Vol. 41 No. 13, pp. 2933-56.

Rebstock, S.E. and Kaula, Y. (1996), "The effectiveness of an analytical hierarchy process in group decision making: a case study", *International Journal of Computer Application in Technology*, Vol. 9, pp. 95-105.

Ross, T.J. (1997), *Fuzzy Logic with Engineering Applications*, International Editions, McGraw-Hill, New York, NY.

Saaty, T.L. (1990), *The Analytic Hierarchy Process*, RWS Publications, Pittsburgh, PA.

Sabel, C.F., Kern, H. and Herrigel, G. (1989), "Collaborative manufacturing: new supplier relations in the automobile industry and the redefinition of the industrial corporation", paper presented at the IMVP International Policy Forum, MIT, May.

Shin, H., Collier, D.A. and Wilson, D.D. (2000), "Supply management orientation and supplier/buffer performance", *Journal of Operations Management*, Vol. 18, pp. 317-33.

Soukup, W.R. (1997), "Supplier selection strategies", *Journal of Purchasing and Materials Management*, Vol. 23 No. 2, pp. 7-12.

Swaminathan, J.M., Sadeh, N.M. and Smith, S.F. (1995), "Information exchange in supply chains", *Technical Report*, The Robotics Institute, Carnegie Mellon University.

Swaminathan, J.M., Smith, S.F. and Sadeh, N.M. (1997), "Modeling supply chain dynamics: a multiagent approach", *Decision Sciences*, Vol. 39 No. 3, pp. 607-32.

Talluri, S. and Sarkis, J. (2002), "A model for performance monitoring of suppliers", *International Journal of Production Research*, Vol. 40 No. 16, pp. 4257-70.

Thrift, P. (1991), "Fuzzy logic synthesis with genetic algorithms", *Proc. 4th Int. Conf. Genetic Algotithms (ICGA)*, San Diego, CA, July, pp. 509-13.

Timmerman, E. (1986), "An approach to vendor performance evaluation", *Journal of Purchasing and Materials Management*, Vol. 22 No. 4, pp. 2-8.

Verma, R. and Pullman, M.E. (1998), "An analysis of the supplier selection process", *Omega–International Journal of Management Science*, Vol. 26, pp. 739-50.

Vokurka, R.J., Choobineth, J. and Valdi, L. (1996), "A prototype expert system for the evaluation and selection of potential suppliers", *International Journal of Operations & Production Management*, Vol. 16, pp. 106-27.

Wang, C.H., Hong, T.P. and Tseng, S.S. (1997), "Knowledge integration by genetic algorithms", *Proc. 7th Int. Fuzzy Systems Association Worlds Cong.*, Vol. 2, pp. 404-8.

Wang, C.H., Hong, T.P. and Tseng, S.S. (1998), "Integrating fuzzy knowledge by genetic algorithms", *IEEE Trans. On Evolutionary Computation*, Vol. 2 No. 4, pp. 138-49.

Yuan, Y. and Zhuang, H. (1996), "A genetic algorithm for generating fuzzy classification rules", *Fuzzy Sets and Systems*, Vol. 84, pp. 1-19.

Zadeh, L.A. (1965), "Fuzzy sets", *Information and Control*, Vol. 8, pp. 338-53.

Zadeh, L.A. (1978), "Fuzzy sets as a basis for a theory of possibility", *Fuzzy Sets and Systems*, Vol. 1, pp. 3-28.

Zimmerman, H.J. (1991), *Fuzzy Set Theory and its Applications*, 2nd ed., Kluwer Academic Publishers, Boston, MA.

Multi-agent architecture for supply chain management

Daniel Roy
Didier Anciaux
Thibaud Monteiro and
Latifa Ouzizi

The authors

Daniel Roy is based at MACSI-INRIA, LGIPM-AGIP, ENIM, Metz, France.
Didier Anciaux, **Thibaud Monteiro** and **Latifa Ouzizi** are all based at MACSI-INRIA, LGIPM-AGIP, Université de Metz, Metz, France.

Keywords

Supply chain management, Strategic planning, Virtual organizations

Abstract

The purpose of this paper is to propose a new approach for the supply chain management. This approach is based on the virtual enterprise paradigm and the usage of multi-agent concept. The base component of our approach is a virtual enterprise node (VEN). The supply chain is viewed as a set of tiers (corresponding to the levels of production), in which each partner of the supply chain (VEN) is in relation with several customers and suppliers. Each VEN belongs to one tier. The main customer gives global objectives (quantity, cost and delay) to the supply chain. The mediator agent (MA) is in charge to manage the supply chain in order to respect those objectives as global level. Those objectives are taking over to negotiator agent at the tier level (NAT). This architecture allows supply chains management which is completely transparent seen from simple enterprise of the supply chain. The use of multi-agent system allows physical distribution of the decisional system. Moreover, the hierarchical organizational structure with a decentralized control guarantees, at the same time, the autonomy of each entity and the whole flexibility.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

 · ISSN 1741-038X
DOI 10.1108/17410380410565339

1. Introduction

In today's increasing global and competitive marketplace, it is imperative that enterprises work together to achieve the expected goals in terms of minimizing the delay of deliveries, the holding costs and the transportation costs. New forms of organizations have emerged, the so-called extended enterprises and virtual enterprises (VEs), in which partners must demonstrate strong co-ordination and commitment capabilities to achieve the desired goals. A VE could be a single enterprise or a regrouping of similar companies (i.e. similar goods).

Today, in a supply chain, manufacturers no longer produce complete products in isolated facilities. They operate as nodes (i.e. single or virtual enterprise) in a network of suppliers, customers, warehouse and other specialized service functions (Davidow and Malone, 1995).

Owing to the high complexity of a whole supply chain, a centralized decisional system seems not be able to manage easily all the necessary information and actions. Moreover, the centralized philosophy is strongly opposed to the decisional autonomy of the supply-chain components (firms). This is why, we propose a more distributed approach in order to adhere to nodes autonomy and to facilitate the management.

Supply chain management needs to integrate two decision levels: planning and control. In planning a supply chain, coherent planning of all actors is needed. This integration not only applies to the material flows from raw material suppliers to finished product delivery but also to the financial flows and information flows from the market (i.e. the anonymous consumers) back to the supply-chain partners. This planning function lies at the tactical level of the supply chain. Control function has a shorter run decision and a smaller focus than planning. Its objectives are restricted on one single enterprise or VE. It lies at the operational level.

The purpose of this paper is to propose a new approach for the supply chain management. This approach is based on the VE paradigm and the usage of multi-agent concept.

The VE is defined as a regrouping of nodes (or entities) which are linked together with information and material flows. Of course, each node could be itself a VE or simple enterprise.

First, the supply chain architecture is defined. We detail our approach in the second part, giving

Received: 27 June 2003
Accepted: 26 February 2004
Part of this work is related to the EU Growth V-CHAIN Project on the design and management of supply chain in the discrete parts manufacturing industry.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

attention to the supply chain three main levels: actors, tiers and global. Then, we focus our approach on the elementary actor level, and finally, we present some conclusions and further research.

2. Supply chain context

2.1 Architecture definition

The supply chain considered in our work can be summarized as follows (Figure 1).

The supply chain is viewed as a set of tiers (corresponding to the nomenclature levels), in which each partner, called a virtual enterprise node (VEN), is in relation with customers and suppliers on the adjacent tiers. We assume that each VEN is only in relationship with its adjacent VENs (no loop between the VENs allowed). So, each VEN belongs to one tier.

The VEN is the base component of this architecture. As mentioned earlier, this VEN could be a single enterprise or a regrouping of similar companies (i.e. similar goods). In that case, each company could transfer a part of its production to others.

The concept of VE was introduced with the aim of widening the concept of the extended enterprise towards a concept of less centralized organization. Contrary to the extended enterprise which is arranged around a decision center, the VE characterizes an independent consortium which links their resources for growing their reactivity regarding the unpredictable environment (Hardwick and Bolton, 1997).

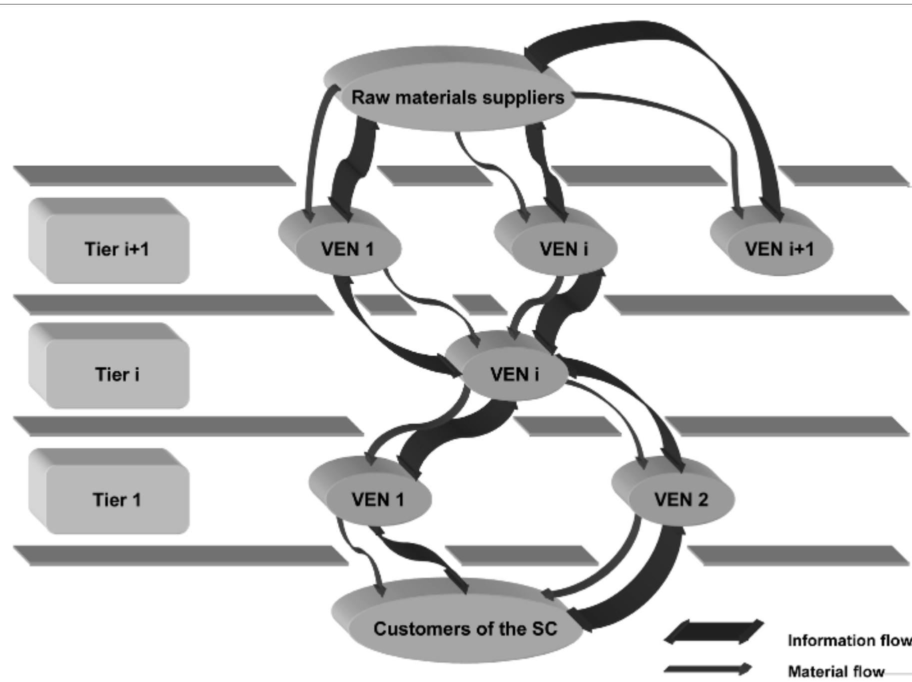
It is assumed that any component can be provided to each VEN by only one supplier VEN without the possibility of changing it by another supplier, except in the case of a longterm disagreement.

To generate a better productivity, these companies need the coordination of the actions which are distributed among autonomous partners (Altersohn, 1992; Rota, 1998; Kjenstad, 1998). Recent research shows a growing interest in studying cooperation relationships among the multiple actors of an industrial architecture (Axelrod, 1992; Rapoport, 1987; Ferrarini *et al.*, 2001; Monteiro and Ladet, 2001b). Cooperation can take various forms. It can be defined as a collaboration between partners, each having equivalent decisional capacity and acting together towards a common objective. One example of collaboration is the co-design in the automotive (Womack *et al.*, 1992) or aeronautical sectors. Cooperation can also be defined as the coordination and synchronization of operations carried out by independent actors (Malone and Crowston, 1994; Monteiro and Ladet, 2001a). Each partner has a limited decision power that corresponds to its action field (Camalot *et al.*, 1997; Camalot, 2000; Huguet, 1994).

2.2 Cost definition and cost negotiation

The problem of VENs is to coordinate decentralized actions and to establish a coherent

Figure 1 Supply chain architecture



Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

planning in real time (planning by considering the variation of forecasting and capacity of VENs). So, at the same time, VENs may assure local and global benefits within the supply chain. Locally, we are interested in optimizing the behavior of each VEN; the objective of each VEN is to minimize purchasing and production costs and also to ensure a positive benefit (Anciaux *et al.*, 2003).

The global benefit of the supply chain is:

$$\sum_{\text{all VENs}} \text{selling} - \sum_{\text{all VENs}} \text{costs} \geq 0 \qquad (1)$$

3. Management architecture definition

In order to benefit, at the same time, from the agility of the distributed approach and from the coordination of the centralized one, we choose to mix these two approaches in a specific architecture.

3.1 Multi-agent paradigm

The intrinsic distribution of the supply chain cannot be managed by only one and single data-processing application. Indeed, the exchanges of information and the behaviors specific to operations of the supply chain members are so complex that they ask for CPU time which can only be shared. Accordingly, it seems to us that only a multi-agent architecture can meet this need (Ferber, 1995; Patriti *et al.*, 1997).

The supply chain is modeled as a multi-agent system (MAS), agents use cooperative negotiation to establish coherent decisions. To limit the negotiation process in terms of iterations, a negotiator agent for each tier *j* of the VE (NAT_j) and a mediator agent (MA) for the whole VE will be used.

The architecture of the system is shown in Figure 2.

3.2 VEN level

VEN is the elementary component of our architecture. VEN is composed by a single or many companies. In that case, those ones gather around a project, either to face competition, or to answer a request largely higher than the individual partners' capacities. These companies commonly exchange among themselves a part or all their orders. This allows each to solve the reoccurring problem of internal production overload. Even if, seen outside, only one company is in direct relation with the customer; it is in fact several companies which answer together the initial offer.

3.2.1 VEN organization

With the reception of a new order from a client, a member of a VEN, qualified principal supplier (PS), evaluates in-house his capacity of answer. If this one cannot ensure the entire induced load, it contacts its partners to absorb the overload. Our approach consists in using for this purpose a virtual space broker agent (VSBA) to manage the overload distribution among the VEN.

A client's order must contain the following information:

- client and principal supplier identifiers (Ct, PS);
- product *i* references (P_i); and
- order characteristics: quality (K), maximum cost ($C_{\max}$), quantity (Q) and due date (D)

A split delivery is possible. In this case, a minimum quantity $Q_{\min}$ has to be delivered at least for D, the rest having to be delivered at the latest to $D_{\max}$. Figure 3 shows this research space (Monteiro and Roy, 2003).

The choice is based on an algorithm for demand estimation (Monteiro *et al.*, 2004). The goal is to decide, using knowledge of the systems current state, if the company (PS) can accept or reject a new demand from its client (Ct). This decision is based on the evaluation of the load on a production center. To determine rapidly in what conditions the company is able to manufacture the new order, a comparison is made between the added load induced by this new manufacturing demand and the idle (unused production capacity) of each planning period (Figure 4).

This analysis is done by focusing on the bottleneck activity[1] of the internal production system.

3.2.2 The virtual space broker agent

The VSBA receives from one of its partners (PS for this command) an initial demand (job request) which contains the following limits for:

- quantity (Q', $Q'_{\min}$),
- delay (D, $D_{\max}$),
- cost ($C'_{\max}$)

Those limits are fixed by the PS according to the part that the PS makes itself.

Then, the VSBA reflects the request on various partners by forwarding request for production without overtime for the date *D*. So, VSBA sends requests with the following form: $\langle Q', D, HS = 0 \rangle$. Each partner i could reply to this request by sending its proposal in terms of quantity and cost (q_i, c_i). That information is used for VSBA's decision. Following the algorithm shown in Figure 5, VSBA is able to answer the PS and share the job between partners.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

Figure 2 Agent organization

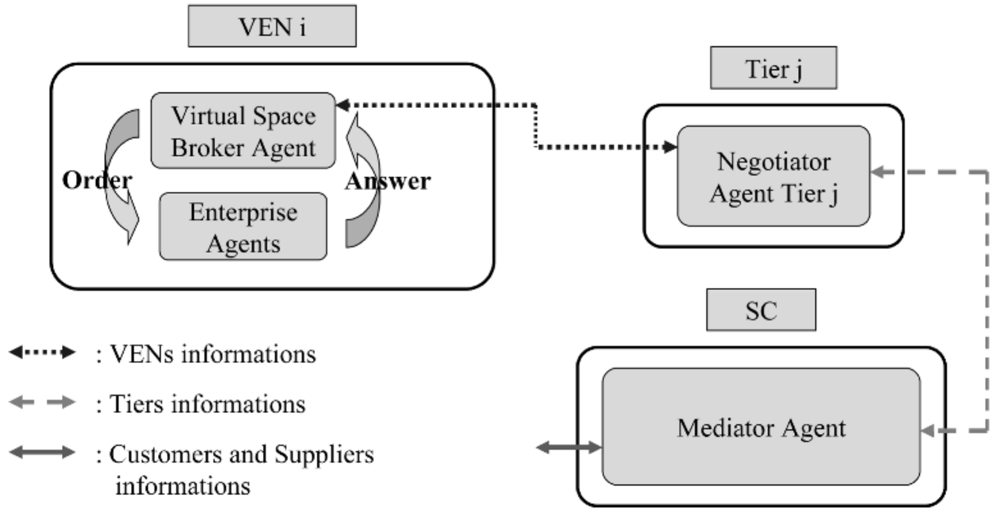
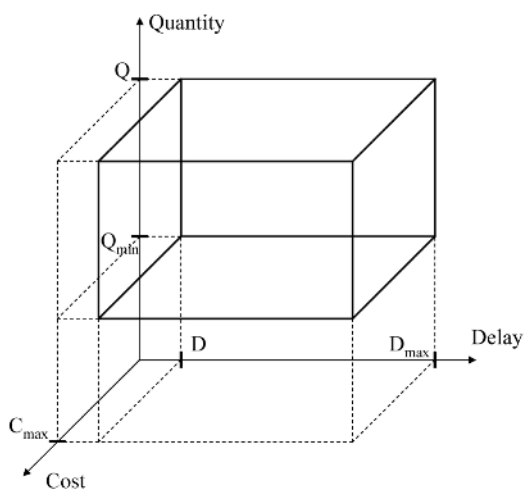


Figure 3 Research space



Then the VSBA has the following four possible options which are the function of partners' answers. They are:

- achieve the job by respecting the whole constraints induced by the order and carry out a complete delivery at D;
- refuse the job, because its induced constraints are too restrictive for the VEN;
- make a second request allowing overtime; and
- research split delivery possibilities for $D_{\max}$ at the latest.

Split delivery consists in supply client the available quantity at D with at least $Q_{\min}$ (case 2) or $Q_{\min+}$ (case 1). $Q_{\min+}$ indicates the sum of the products carried out by the partners retained for the first delivery. Answers not allowing to obtain strictly $Q_{\min}$, quantity retained for $Q_{\min+}$ may be higher than $Q_{\min}$. The missing quantity is delivered for the date $D_{\max}$ at the latest.

This new request involves an update of the variables of quantity and cost.

$$\begin{aligned} &\text{Case 1}: \quad Q' = Q' - Q'_{\min+} \\ &\text{Case 2}: \quad Q' = Q' - \sum q_i \end{aligned} \tag{2}$$

$$\begin{aligned} &\text{Case 1}: \quad C'_{\max} = C'_{\max} - \sum^{Q'_{\min}} c_i \\ &\text{Case 2}: \quad C'_{\max} = C'_{\max} - \sum c_i \end{aligned} \tag{3}$$

Each member of the VEN could reply to this request by sending its proposal in terms of quantity, cost, and date (q_i, c_i, d_i).

The VSBA analyzes answers of the partners according to the process shown in Figure 6.

3.2.3 The single enterprise VEN case

In principle, each VEN is faced with:

(1) internal constraints related to its capacity limits; and
(2) external constraints, related to its:
    - customer VENs demanding products with a minimal delay at lower cost and at a required quality level; and
    - supplier VENs having also constraints of lead times and costs.

The planning and negotiation process of this type of VEN is shown in Figure 7.

To face variations in quantities that the VEN must deliver to its customers, the negotiator agent can reply with the followings:

- I can deliver without any problem;
- I can but with additional efforts (using overtime or subcontracting);

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

Figure 4 Load of a production center and new demand estimation process

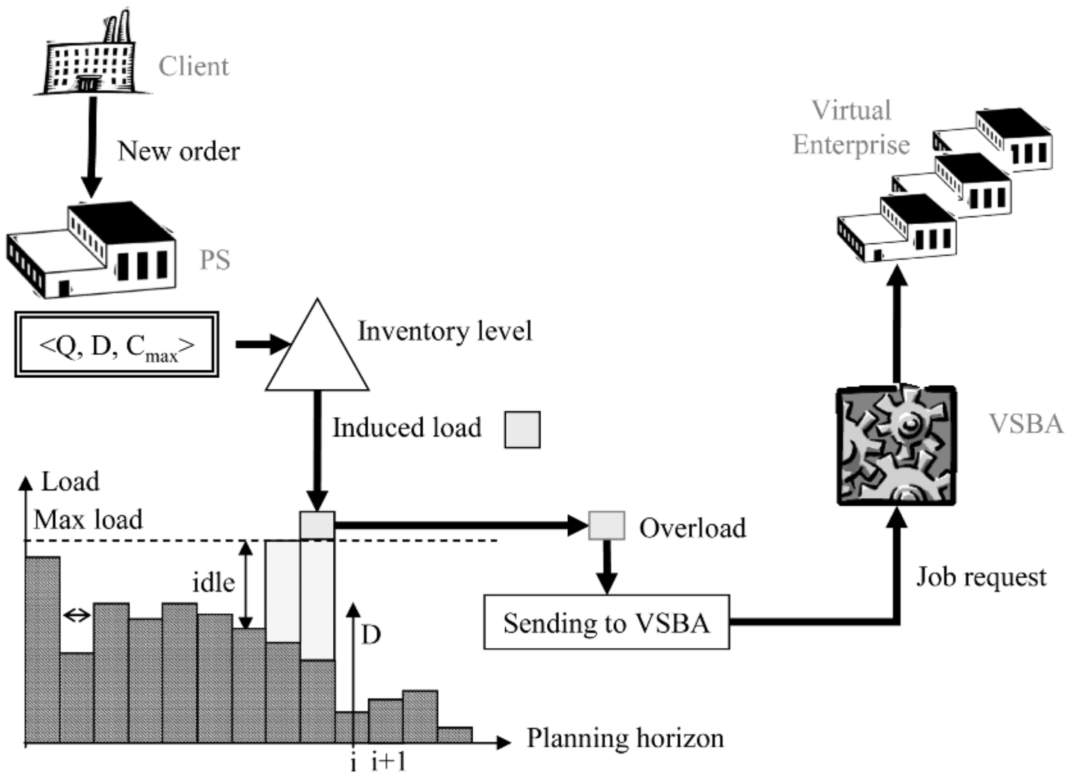


Figure 5 VSBA decision algorithm

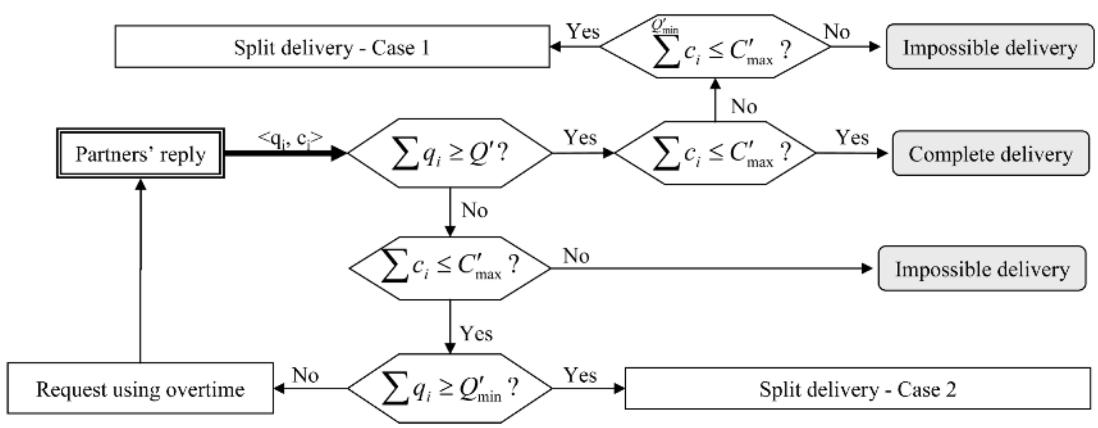
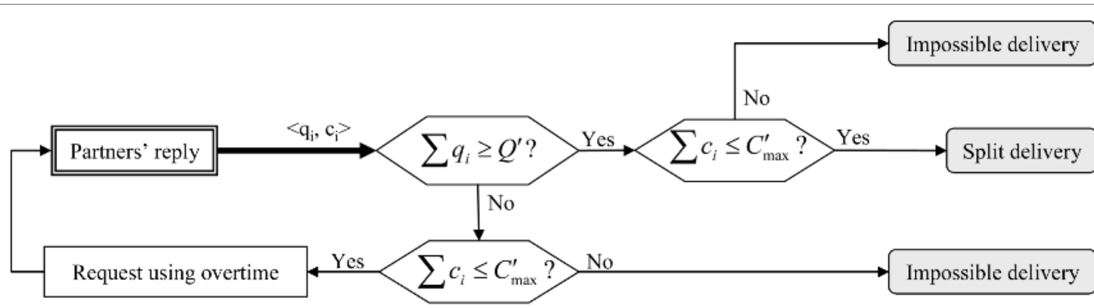
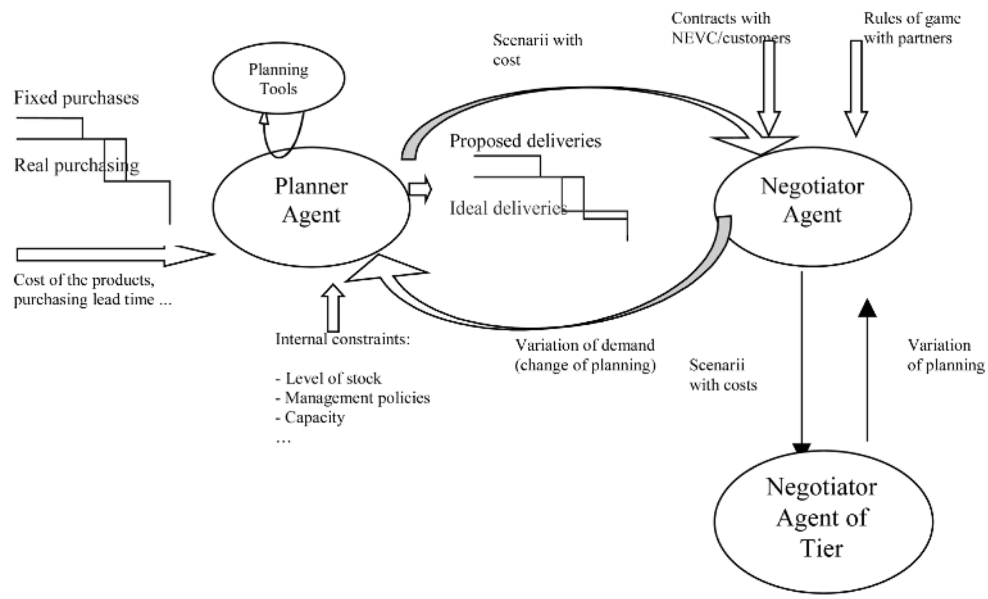


Figure 6 Search for a split delivery solution



Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

Figure 7 The planning and negotiation process of a VEN



- I agree if you fully or partially compensate me with all the over costs, especially if the quantities requested do not respect contracts; and
- I can supply you – advance future arrivals of components in entry for backward planning – move back the deliveries of certain products for the direct planning.

Otherwise, it is assumed that there is a possibility that the stocks planned for another customer can be delivered to another one which have a great penalty for delays, with compensation of possible over costs.

The NAT takes the set of propositions and chooses propositions with the minimal cost for the associated tier.

3.3 Tier level

3.3.1 Rolling plan and forecasting evolutions

Each VEN of the first tier collects information about future sales from the customers, generally with uncertainty estimation. The forecasts are transmitted to all the VENs of the supply chain. It is assumed that agreements are signed between VENs of the first tier and customers on one hand, and on the other between partners of the SC. Thus, it is assumed that information is always shared truthfully (trusted relationships) (Gavirnenei *et al.*, 1999; Cachon and Lariviere, 2001).

On the basis of forecasting data and contracts established, each VEN makes its planning. In the event of unforeseen production problems of a VEN, or of forecasting change, it must commit with its current customer and supplier VENs, so that they try to overcome the problem collectively, which ensures the continuity of the production and global non-stop of the manufacturing chains.

Using a rolling horizon (Ouzizi *et al.*, 2003), the VENs do the planning with new forecasting (Figure 8).

3.3.2 Planning the supply chain

It is assumed that:

(1) in the last unit of time, planning over the supply chain are negotiated and coherent; and
(2) at the first of the next period of planning, each VEN of the first level must readjust its planning according to the demands variation for finished product, or of possible risks that can occur during the period.

Thus, the consequences are:

- to correct forecasts of finished products from the period 1 to $T - 1$ (these forecasts are the same corresponding to periods 2 to T with corrections);
- to add a new forecast for the period T; and
- to update stocks of all upstream and downstream components of the supply chain.

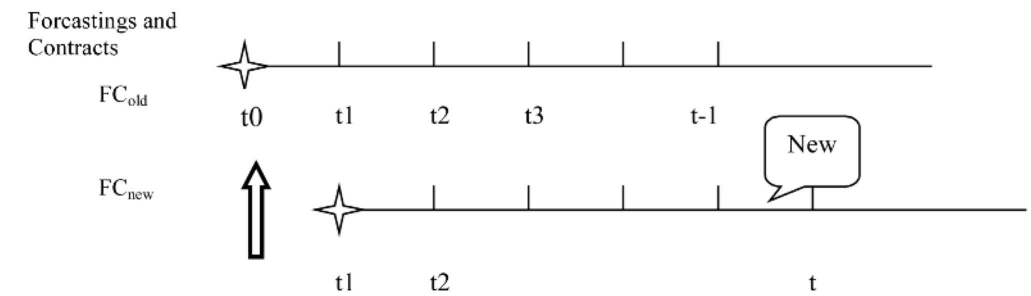
The problem of each VEN is to determine if it is sufficient to add one period for the planning in order to cope with variations or if it is necessary to change more or less the previous planning so as to find coherent and negotiable planning.

To cope with this problem, the following procedure is proposed:

A0 – Different tiers of the supply chain are distinguished, which are denoted by rows. (**NR** is the highest number of rows corresponding to the VENs at the last tier).

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 745–755

Figure 8 Rolling horizon for planning



A1 – For each tier from NR down to 1 do
Preliminary work for each tier
For each VEN of the tier do
It is assumed that the due date of products manufactured by the VEN are fixed
For each combination of parameters (costs, penalties, possible delays…) do
Construct the backward planning corresponding to the due date deliveries fixed
Endfor each combination of parameters
Endfor each VEN

For the modification of due date deliveries corresponding to the same component and used by several VENs of one level, the negotiator agent (NAT_{row}) of the tier checks if requests anticipated for some nodes are delayed for others. In this case, the problem will not have a serious incidence upstream. Having the sum of all orders and variations, the NAT makes a choice of a planning for each VEN of the tier by taking into account holding costs, production costs corresponding to this tier and perturbations caused.

It is thus advisable here to propose a simple method for the choice of planning to be retained (this method can be parameterized to give different results if it is used several times). The definite choice of backward planning makes possible to give the due date deliveries of products manufactured for the adjacent upstream tier.

Endfor each l

A2 – In the case where each VEN does not need to place orders of components in the past, the negotiator agent of the tier (NAT) has a set of planning established in A1 that are negotiated and consistent. The NAT selects planning on the basis of the two objectives cited before. If these objectives are satisfied, then everything is ok; otherwise, the A1 procedure starts again with VENs or the NAT changing weights of some penalties.

If backward planning obtained use negative periods, then the VENs establish direct planning. Thus, VENs replace negative times by 0, so that the due dates for purchased products from suppliers of the virtual enterprise are fixed.

A3 – For tier varying from 1 to NR do
Preliminary work for each tier
For each VEN of the tier do
It is assumed that the due dates of purchased products are fixed
For each combination of parameters chosen by the VEN or the NAT do
Construct the direct planning taking into account of products that have been manufactured and the values of the two criteria (costs and penalties)
Endfor each combination
Endfor each VEN

Because it is assumed that any component is provided from one VEN within the SC, it is not possible to obtain compensation between VEN's of the same tier. Thus, in choosing planning, the NAT must not systematically disadvantage always the same VEN and it has to distribute delays over the various customers of each VEN. It is thus advisable here to propose a simple method for the choice of planning (this method can be parameterized to give different results if it is used several times). The definite choice of the direct planning makes possible to give the due date deliveries of components for the adjacent downstream tier.

Endfor each row

A4 – At the end of step A3, consistent planning of products to be delivered to external customers are obtained but with delays (acceptable or not) as well as the costs and over cost at each VEN. It is then advisable to decide if each one is satisfied by the whole set of consistent planning found and to stop the procedure or if it is necessary to start again in A3 or in A1 by changing penalties or parameters so as to construct a new set of consistent planning.

By limiting the computing time of each direct or backward planning, the number of combinations of parameters and the computing time of the procedures to select planning (number of calls to

procedures A1-A4) are bounded by the number of VENs. Thus, we obtain a global algorithm in which the computing time is bounded by the number of VENs and the number of periods. It is therefore, sufficient to call the method for elaborating consistent planning in a limited number of times to find consistent and negotiated planning in a reasonable timeframe.

3.4 Supply chain level

The supply chain is modeled as a MAS; agents use cooperative negotiation to establish a coherent planning. To limit the negotiation process in terms of iterations, a negotiator agent for each tier i of the supply chain (NAT_i) and a MA for the whole supply chain will be used.

The architecture of the system is shown in Figure 9.

4. Simple industrial illustration

In this part, we illustrate our approach with the following industrial organization. After organization presentation, an order life cycle is simulated.

4.1 Example organization

This example is based on the bronze tap production. In order to facilitate our approach comprehension, we keep only the main components of a sold tap (called PF in Figure 10):

- one Bronze body (called SC BBA);
- two O ring (called SC BA); and
- one Blister (called SC A).

Those components are, respectively, themselves made of:

- base metals (copper and tin) (called SC BBAA);
- rubber (called SC BAA); and
- carton (called SC AA).

All those elements constitute the product breakdown structure (PBS) of bronze tap.

To each element of the PBS corresponds a supplier entity. This entity could be a single enterprise or a regrouping of similar companies. The breakdown structure and corresponding firms allow us to construct the corresponding tap's supply chain. The supply chain is viewed as a set of tiers, in which each partner is in relation with customers and suppliers on adjacent tiers. As Figures 2 and 9 show, tier relations are supported by the MA. All those adjacencies structure supply chain pattern of tiers. This, example, organization can be summarized as follows (Figure 11).

We focus our illustration on one VEN constituted by bronze producers (squared on Figure 11). This VEN is, in fact, an association of five bronze plants, in which the PS is the only enterprise visible by network partners.

4.2 Order life cycle

The PS receives a new order form Rob plant with the following characteristics, which define the quantities, delays and maximum cost allowed by the client: $\langle [1,000, 750], [50, 55], 100 \rangle$. This request comes from the A1 algorithm described in Section 3.3.2.

The PS internal analysis concludes that it can only produce 500 unities at a cost of 45 for the given deadline. So, PS sends a message to its VSBA with the following characteristics: $\langle [500, 250], [50, 55], 55 \rangle$. The VSBA sends

Figure 9 Global scheme of the VE

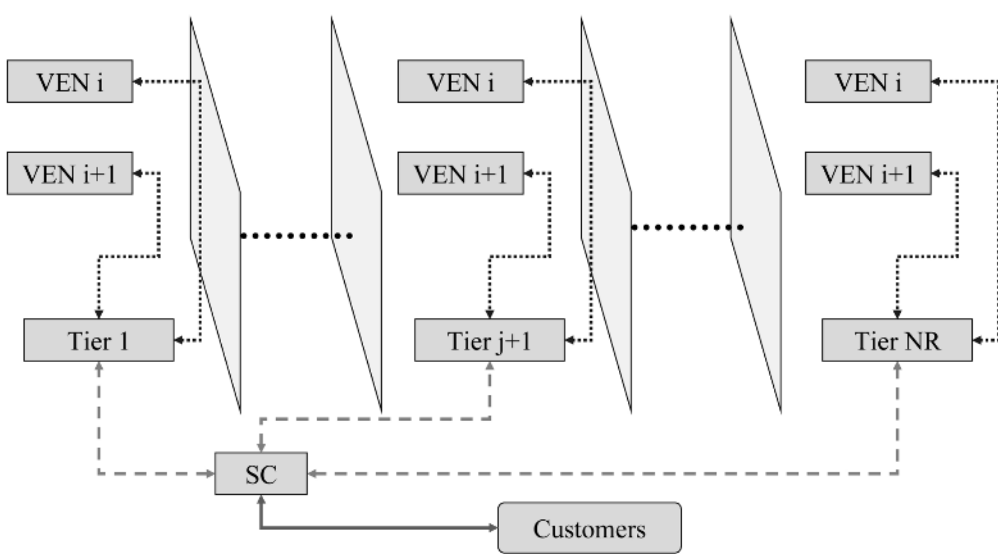
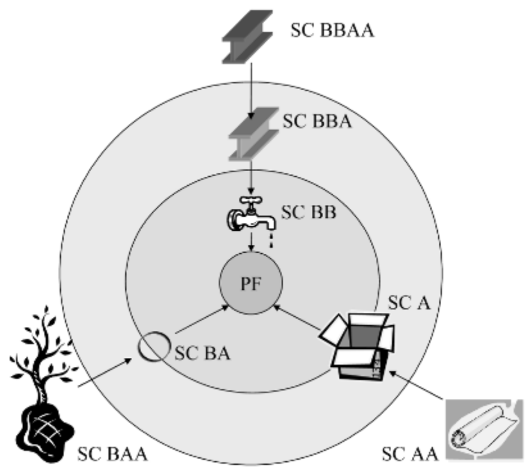


Figure 10 Sold tap components



requests ($\langle 500, 50, HS = 0\rangle$) to the four partners to know what their capacities are.

The answers of the partners are listed in Table I.

In the VSBA, the answers analysis leads to a Split delivery – case 2 (Figure 5). Indeed, the total quantity is under 500, the total cost is under 55 and the total quantity is higher than 250. For the first delivery, VSBA chooses the partners shown in Table II, according to their individual performances (Monteiro and Roy, 2003).

After those affectations, 240 unities have to be produced at a total cost of 22 for the date 55. So, VSBA sends the request $\langle 240, 55, HS = 0\rangle$ for the last delivery.

The answers of the partners are listed in Table III.
VSBA uses the process shown in Figure 6 to analyze those answers. It concludes that over time has to be used. Indeed, total quantity is under 240 and maximum cost is not reached. VSBA sends the request $\langle 240, 55, HS = 1\rangle$.

Answers taking into account overtime are listed in Table IV.

VSBA analysis concludes with a possible split delivery. Indeed, total quantity could reach 240 without exceeding the maximum cost of 22. So, for the last delivery, VSBA chooses the partners shown in Table V.

Finally, this order could be supported by the VEN with the work distribution shown in Table VI.

With those two deliveries, the total quantity is 1,000 unities at a cost of 99.

This work distribution is sent to tier 2 negotiator agent to analyze coordination problem using O ring plant and Blister plant responses (A1 algorithm). If tier 2 does not generate trouble, all those information are forwarded to tier 1 partner: Rob plant. On the contrary, if coordination problem is detected, tier 2 negotiator agent (using A3 algorithm) sends modification request to upper tier (Rob plant).

5. Conclusion and future research

New industrial architecture organization, based on cooperation, highlights the problem of flow control and management by independent decision centers. Decision distribution along the supply chain needs coherence between partners to achieve better productivity and greater reactivity.

The elementary actors of the supply chain that we had described here could have two different forms. First, it could be a single enterprise in which a planner agent allows a dynamical planning based on the global cost of the supply chain. So, each partner is able to elaborate planning according to unforeseen orders, assuming that quality-cost-delay framework contracts have previously been drawn up between the various partners of the supply chain. Second, the VE could be constituted by many autonomous enterprises with similar productions. This second approach involves one agent by enterprise and a VSBA helping to the load

Figure 11 Supply chain architecture

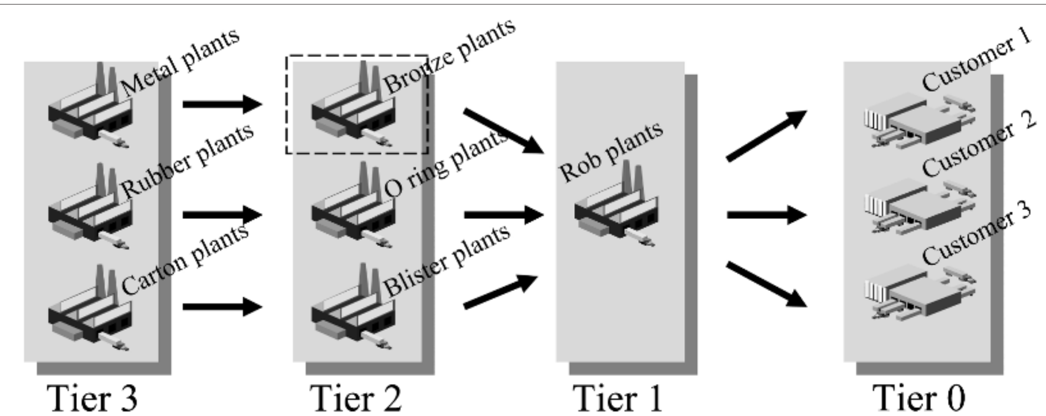


Table I Partners' answers #1

Partner	Quantity	Cost
#1	100	8
#2	60	5
#3	100	12
#4	100	10

Table II Partners' choice #1

Partner	Quantity	Cost	Performance	Rank	Retained
#1	100	8	0,08	#1	Yes
#2	60	5	0,083	#2	Yes
#3	100	12	0,12	#4	No
#4	100	10	0,1	#3	Yes

Table III Partners' answers #2

Partner	Quantity	Cost
PS	30	3
#1	100	8
#2	60	5
#4	40	5

Table IV Partners' answers #3

Partner	Quantity	Cost
PS	70	8
#1	150	13
#2	90	8
#3	40	6
#4	90	12

Table V Partners' choice #2

Partner	Quantity	Cost	Performance	Rank	Retained
PS	70	8	0,114	#4	No
#1	150	13	0,083	#1	Yes
#2	90	8	0,086	#2	Yes
#3	40	6	0,15	#5	No
#4	90	12	0,13	#3	No

Table VI Final work distribution

	First delivery (Date 50)		Last delivery (Date 55)	
Partner	Quantity	Cost	Quantity	Cost
PS	500	45	0	0
#1	100	8	150	13
#2	60	5	90	8
#4	100	10	0	0
Total	760	68	240	21

distribution. On the supply chain view, those two approaches are analogous.

These actors integrate an architecture guaranteeing, at the same time, robustness and agility of the supply chain.

The negotiator agent, in relation with the tier level, and MA, in relation with the supply chain level, permit the use of rolling plan and limit the negotiation process in terms of iterations.

Some evolutions of this system which only concerns a supply network, could be extended to the distribution network. Moreover, the multi-sourcing (multi-VEN) possibilities are not implemented yet and could be studied further.

Note

1 We call bottleneck activity, activity which most restrains the load in the internal production process.

References

Altersohn, C. (1992), *De la sous-traitance au partenariat industriel, dynamiques d'entreprises,* Édition l'Harmattan.

Anciaux, D., Ouzizi, L. and Portmann, M.C. (2003), "Planification d'une chaine logistique par négociation", *Proceedings of the 5th International Industrial Engineering Conference*, Quebec.

Axelrod, R. (1992), *Donnant, donnant: une théorie du comportement coopératif,* Édition Odile Jacob.

Cachon, G.P. and Lariviere, M.A. (2001), "Contracting to assure supply: how to share demand forecasts in a supply chain", *Management Science*, Vol. 47 No. 5, pp. 629-47.

Camalot, J.P. (2000), "Aide à la décision et à la coopération en gestion du temps et des ressources", Thèse de l'Institut National des Sciences Appliquées, Toulouse.

Camalot, J.P., Esquirol, P., Huguet, M.J. and Erschler, J. (1997), "Aide à la décision et à la négociation dans un problème de gestion de production distribuée", *Journées du Groupement de Recherche en Productique*, Cachan.

Davidow, W. and Malone, M. (1995), *L'entreprise à l'âge du Virtuel.* MAXIMA, Collection Institut du Management d'EDF et de GDF, Paris.

Ferber, J. (1995), *Les Systèmes Multi-Agents – Vers une Intelligence Collective*, InterEditions, Paris.

Ferrarini, A., Labarthe, O. and Espinasse, B. (2001), "Modélisation multi-agents de chaînes logistiques", *Proceedings of the 4th International Industrial Engineering Conference*, Aix-Marseille, pp. 1165-74.

Gavirnenei, S., Kapuscinski, S.R. and Tayur, S. (1999), "Value of information in capacitated supply chains", *Management Science*, Vol. 45 No. 11, pp. 16-24.

Hardwick, M. and Bolton, R. (1997), "The industrial virtual enterprise", *Communications of the ACM*, Vol. 40 No. 9, pp. 59-60.

Huguet, M.J. (1994), "Approche par contraintes pour l'aide à la, décision et à la coopération en gestion de production", Thèse de l'Institut National des Sciences Appliquées, Toulouse.

Kjenstad, D. (1998), "Coordinated supply chain scheduling", Thèse soutenue au department of Production and quality engineering Norwegian university of science and technology.

Malone, T.W. and Crowston, K. (1994), "The interdisciplinary study of coordination", *ACM Computing Survey*, Vol. 26 No. 1.

Monteiro, T. and Ladet, P. (2001a), "Formalisation de la coopération dans le pilotage distribué des flux interentreprises, Application à une entreprise de production de biens", *Numéro spécial – pilotage distribué, JESA*, Vol. 35 Nos 7/8, pp. 963-89.

Monteiro, T. and Ladet, P. (2001b), "Modélisation d'une architecture industrielle pour le pilotage distribué des flux interentreprises", *Proceedings of the 4th International Industrial Engineering Conference*, Aix-Marseille.

Monteiro, T. and Roy, D. (2003), "Architecture de pilotage semi-distribuée de l'entreprise virtuelle", *Proceedings of the 5th International Industrial Engineering Conference*, Quebec.

Monteiro, T., Ladet, P. and Bouchriha, H. (2004), "Multi-criteria negotiation for a distributed control of a client/provider relationship", *Journal of Decision System*, Vol. 13 No. 1, pp. 63-89.

Ouzizi, L., Anciaux, D., Portmann, M.C. and Vernadat, F. (2003), "A model for co-operative planning using a virtual enterprise", *Proceedings of the 6th International Conference on Industrial Engineering and Production Management*, Porto.

Patriti, V., Schäfer, K., Ramos, M., Charpentier, P., Martin, P. and Veron, M. (1997), "Multi-agent and manufacturing: a multilevel point of view", *Proceedings of the Computer Application in Production and Engineering*, Detroit, MI.

Rapoport, A. (1987), *Game Theory as a Theory of Conflict Resolution*, Kluwer Academic Press, Dordrecht.

Rota, K. (1998), "Coordination temporelle de centres gérant de façon autonome des ressources – Application aux chaînes logistiques intégrées en aéronautique" Thèse de l'Université Paul Sabatier, Toulouse.

Womack, J.P., Jones, D.T. and Roos, D. (1992), *Le système qui va changer le monde: une analyse des industries automobiles mondiales dirigée par le MIT*, Dunod.

Supply chain scheduling using distributed parallel simulation

Juha-Miikka Nurmilaakso

The author

Juha-Miikka Nurmilaakso is based in Department of Computer Science and Engineering, Helsinki University of Technology, Finland.

Keywords

Supply chain management, Production scheduling, Simulation

Abstract

In a supply chain, an order often connects a number of companies whose schedules affect the success of the order. This paper proposes distributed supply chain scheduling in the agent architecture instead of centralised supply chain scheduling. The companies communicate through their agents that share only the information relevant to the supply chain scheduling. This scheduling relies on distributed parallel forward simulation in which simple messages are exchanged between the agents periodically. According to these messages, each agent simulates the production orders of its company and receives and sends messages about the purchase and sale orders. This synchronises the simulation of the agent with the simulations of the other agents. Distributed simulation reduces the competitor's opportunities to manipulate the company's performance through the schedules of its suppliers and customers. Although distributed simulation does not optimise the schedules, it is capable of finding feasible schedules.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 756–770
 · ISSN 1741-038X
DOI 10.1108/17410380410565348

Introduction

Supply chain scheduling plays an important role in supply chains (Little *et al.*, 1995). Traditionally, centralised supply chain scheduling has been applied to this purpose. However, if the supply chains cross and a company is a participant in multiple supply chains at the same time, centralised scheduling may reveal the company's critical information to its competitors. Distributed scheduling provides a solution to this problem.

Non-deterministic polynomial complexity is typical of scheduling problems (Blazewicz *et al.*, 1983). Therefore, it is often most practical not to search for an optimal schedule but for a feasible schedule that is as good as possible. Finding a feasible schedule using a manual approach is almost as difficult as finding an optimal schedule using an automatic approach. This is much more challenging in distributed scheduling than in centralised scheduling. In addition to the manual approach, there are three automatic approaches to distributed scheduling (Seilonen, 1997). These are contract net (Maturana and Norrie, 1997; Shaw, 1987; Smith, 1980), distributed constraint satisfaction (Miyashita, 1998; Sycara *et al.*, 1991; Yokoo *et al.*, 1998), and distributed simulation. Since distributed simulation is simple, can deal with precedences, and cannot be trapped into infinite loops, it is the chosen approach.

This paper presents a model, a method, and a prototype of an agent system using distributed simulation in distributed supply chain scheduling. The results are based on both conceptual and constructive research. Simulation has often been employed at the strategic level in supply chains (Chan *et al.*, 2002) or in studying supply chain dynamics (Huang *et al.*, 2003), whereas this paper emphasises its role in supply chain scheduling at the operative level. Firstly, the paper motivates distributed scheduling and presents a conceptual model to formalise a mathematical model of supply chain scheduling that is based on the resource-constrained project scheduling problem (RCPSP). Secondly, this paper addresses the distributed simulation method. Finally, the paper presents a prototype that solves supply chain scheduling using distributed parallel forward simulation in the agent architecture. In the client-server architecture, a client produces and a server

Received: 2 July 2003
Accepted: 4 February 2004
This work was partly funded by the National Technology Agency of Finland through the project SUCCESS: Supply Chain Wide Scheduling System. The author thanks his colleagues Kalle Kuhakoski, Veli-Pekka Mattila and Ilkka Seilonen as well as his industrial partners Planar International and Solagem.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

reacts to stimuli. In the agent architecture, an agent both produces and reacts to stimuli.

Background

A supply chain means a flow of goods, services, information, and money through different sites. Supply chain management (SCM) controls this flow from raw-material production to final product retailing (Jansson *et al.*, 2001). It performs accurate assignment of the resources and exact synchronisation of the activities in the supply chain. SCM has potential for considerable positive or negative business impacts. In the best case, it enables an efficient supply chain that reduces the response time, lead time, and inventory level, and also improves the capacity utilisation. In the worst case, its failure leads to redistribution of revenues and risks that are costly and create no new value. Scheduling is necessary if a participant in a supply chain wants to know whether it is profitable or even possible to deliver an order. On the other hand, online real-time scheduling has much to give when contingencies have effects on the availability of resources, e.g. due to new orders or machine breakdowns. This is very useful for a resource-critical sub-chain where problems impair the performance of all participants in the supply chain.

Although a supply chain consists of flows through different participants, these participants are not only different sites within the same company, but they often belong to different companies. The former case is related to an internal supply chain because one participant has authority over the other participants. The latter case is related to an external supply chain because all participants have autonomy. The latter case is in many ways more difficult than the former one. A supply chain is largely based on co-operation, and competition is not necessary between the companies but between the supply chains. However, supply chains are not isolated, but they often cross and form a supply network. Figure 1 shows that a company may have a number of sites and it may be involved in a number of supply chains at the same time.

The company co-operates with customers and suppliers that may compete with each other. Similarly, these customers and suppliers may co-operate with the competitors of the company. There is a trade-off between competition and co-operation. Therefore, the basic challenges originate from the difficulties in balancing competition and co-operation between the participants in the supply chain.

Scheduling is important in the assignment of resources and the synchronisation of activities, but its use is not self-evident in SCM. Centralised scheduling requires information sharing that may force the participant to reveal its critical information (Jansson *et al.*, 2001). In centralised scheduling, the scheduler participant receives the other participants' production information, schedules its own and the others' productions, and sends back the schedules to the other participants. There is no problem in internal supply chains. However, this can be very problematic if a participant is involved in multiple external supply chains. For example, company X has a competitor, Y, who is a supplier of X's customer or a customer of X's supplier. There is often both co-operation and competition. A company that performs centralised scheduling may manipulate its competitors through its suppliers' and customers' schedules. This is a potential barrier to the use of supply chain scheduling. Therefore, distributed scheduling provides an attractive approach.

Model

Conceptual model

A conceptual model is composed of partners, orders, activities, precedences, resources, and allocations. Figure 2 shows the conceptual model from the company's $[h]$ viewpoint using the Object Modeling Technique (OMT).

A partner $[h'] \neq [h]$ is a supplier if it sells a product to the company $[h]$. Respectively, if partner $[h''] \neq [h]$ buys a product from this company, it is a customer.

An order $[h, i]$ is classified as either an internal or an external order. Internal orders are related to the company's production, whereas external orders are related to its sales to customers and its purchases from suppliers, i.e. they are sale orders from the suppliers' viewpoint and purchase orders from the customers' viewpoint. An internal order consists of at least one internal activity, whereas an external order comprises two external activities.

An activity $[h, i, j]$ consists of activity periods $D'[h, i, j] \geq 0$, which have a unit duration. Its lower time bound, i.e. release date, $T'[h, i, j]$ is the earliest schedule period in or after which the activity should be started, and its upper time bound, i.e. due date, $T''[h, i, j] \geq T'[h, i, j] + D'[h, i, j]$ is the latest schedule period in or before which the activity should be finished. These time bounds are given or they can be deduced by applying the critical path method (CPM). An internal activity is either a non-preemptive activity or a preemptive activity. The non-preemptive activity has a fixed duration $D'[h, i, j] \geq 1$ and cannot be interrupted when it is being executed. The preemptive activity has a

Figure 1 Competition and co-operation in a supply network

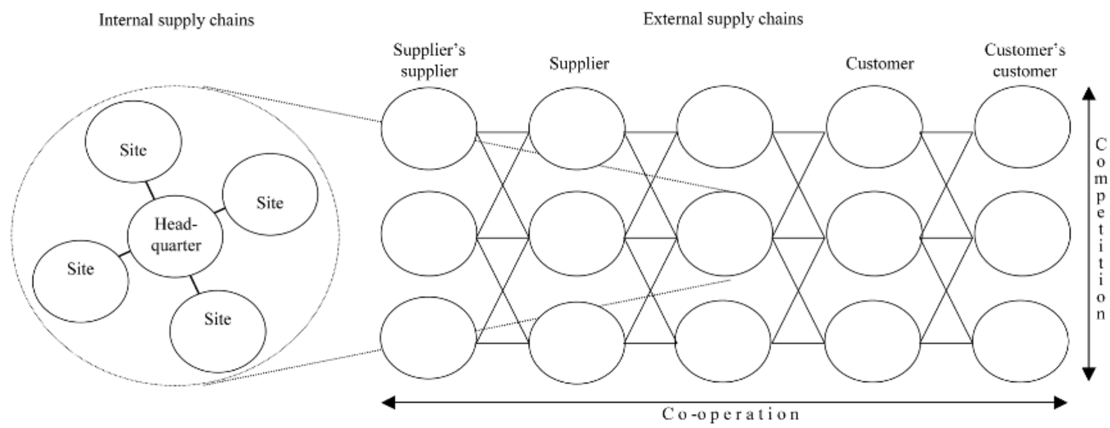
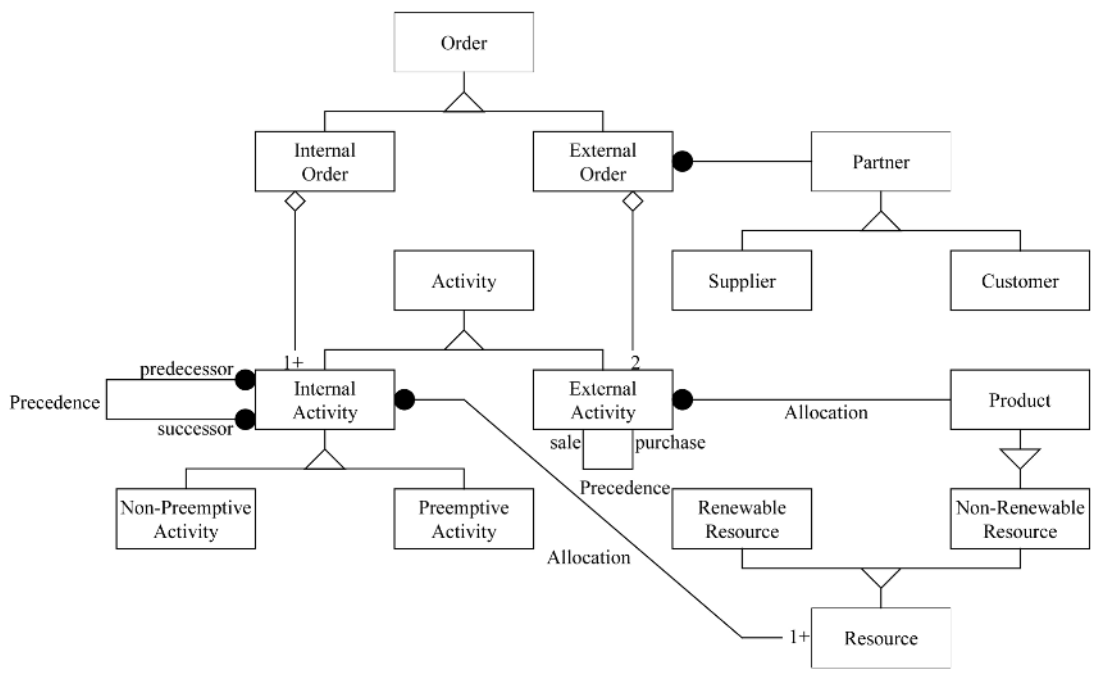


Figure 2 Conceptual model



minimum duration $D'[h,i,j] \geq 2$ as well as a maximum duration $D''[h,i,j] > D'[h,i,j]$, which limits the duration of the interruptions. An external activity has no duration $D'[h,i,j] = 0$.

A precedence forces two activities to be executed in a given order. An internal precedence $[h,i,j',j'']$ binds together a predecessor activity $[h,i,j']$ and a successor activity $[h,i,j'']$ with a delay $\mathrm{D}[h,i,j',j''] \geq 0$. The successor (predecessor) should not be started (finished) until all its predecessors (successors) have been finished (started). Internal activities and internal precedences form an activity network of an internal order. The activity network and the process are regarded as synonymous in this model.

An external precedence $[h',i',j',h'',i'',j'']$ connects a sale activity $[h',i',j']$ and a purchase activity $[h'',i'',j'']$ with a delay $\mathrm{D}[h',i',j',h'',i'',j''] \geq 0$ when a company $[h]$ is either a supplier $[h'] = [h]$ or a customer $[h''] = [h]$. A sale activity, a purchase activity, and an external precedence form an activity network of an external order.

A resource $[h,k]$ is either renewable or non-renewable. A renewable resource, e.g. people and machines, is non-storable, whereas a non-renewable resource, e.g. materials and tools, is storable. In every schedule period $[t]$, the renewable resource has periodic availability $\mathrm{R}[h,k,t] \geq 0$, whereas the non-renewable resource has initial availability $\mathrm{R}[h,k] \geq 0$. A product is a

special case of a non-renewable resource. An internal activity can allocate all these resources, whereas an external activity allocates only one product.

An allocation $[h, i, j, k, d]$ takes place when the activity $[h, i, j]$ uses or consumes (replenishes) the renewable or non-renewable resource or product $[h, k]$ during the activity period or in the start (end) of the activity period $[d]$ by amount $\mathrm{R}[h, i, j, k, d] \geq 0$ ($\mathrm{R}[h, i, j, k, d] < 0$). In fact, the purchase activity only consumes and the sale activity replenishes a product.

Mathematical model

The mathematical model of supply chain scheduling originates from RCPSP. The basic model of Pritsker *et al.* (1969) provides a starting point after extensions. Non-renewable resources and preemptive activities are well-known extensions, whereas non-renewable resources and products, which can be consumed and replenished, are more or less new extensions to this model. The mathematical model comprises three kinds of variables, four kinds of constraints, and two kinds of objectives. The schedule horizon spans from T' to $T'' \geq T' + 1$ for every company in a supply chain.

Variables

Each non-preemptive or external activity $[h, i, j]$ has a variable $x[h, i, j, t] \in \{0, 1\}$ to start this activity in the schedule period $[t] = T', \ldots, T'' - D'[h, i, j]$. In comparison, each preemptive activity has a variable $x[h, i, j, t, d] \in \{0, 1\}$ that indicates the start of the activity period $[d] = 0, \ldots, D'[h, i, j] - 1$. Respectively, a variable $v'[h, i, j] \geq 0$ measures that the activity has been started too early, and $v''[h, i, j] \geq 0$ that it has been started too late. In addition to these variables, there are auxiliary variables for the start equation (1a), finish equation (2a), and resource allocation equation (3a) of the non-preemptive or external activity as well as for the start equation (1b), finish equation (2b), and resource allocation equation (3b) of the preemptive activity.

$$s[h, i, j] = \sum_{t=T', \ldots, T''-D'[h,i,j]} t \star x[h, i, j, t] \tag{1a}$$

$$s[h, i, j] = \sum_{t=T', \ldots, T''-D'[h,i,j]} t \star x[h, i, j, t, 0] \tag{1b}$$

$$f[h, i, j] = \sum_{t=T', \ldots, T''-D'[h,i,j]} t \star x[h, i, j, t] + D'[h, i, j] \tag{2a}$$

$$f[h, i, j] = \sum_{t=T'+D'[h,i,j]-1, \ldots, T''-1} t \star x[h, i, j, t, D'[h, i, j] - 1] + 1 \tag{2b}$$

$$\begin{aligned} r[h, i, j, k, t] = \sum_{d=0, \ldots, \max\{0, D'[h,i,j]-1\}} (&\max\{0, \mathrm{R}[h, i, j, k, d]\} \\ &\star x[h, i, j, t-d] + \min\{0, \mathrm{R}[h, i, j, k, d]\} \\ &\star x[h, i, j, t-d] - \min\{1, D'[h, i, j]\}) \end{aligned} \tag{3a}$$

$$\begin{aligned} r[h, i, j, k, t] = \sum_{d=0, \ldots, D'[h,i,j]-1} (&\max\{0, \mathrm{R}[h, i, j, k, d]\} \\ &\star x[h, i, j, t, d] + \min\{0, \mathrm{R}[h, i, j, k, d]\} \\ &\star x[h, i, j, t-1, d]) \end{aligned} \tag{3b}$$

Hard constraints

Each non-preemptive and external activity equation (4a) as well as each activity period of the preemptive activity equation (4b) is executed once. Only the preemptive activity requires that its first activity period is executed before its second activity period and so on equation (5), and the time span between the start and finish of the non-preemptive activity is limited by the maximum duration equation (6).

$$\sum_{t=T', \ldots, T''-D'[h,i,j]} x[h, i, j, t] = 1 \tag{4a}$$

$$\sum_{t=T'+d, \ldots, T''-D'[h,i,j]+d} x[h, i, j, t, d] = 1 \tag{4b}$$

$$\sum_{t=T'+d, \ldots, T''-D'[h,i,j]+d-1} t \star (x[h, i, j, t, d+1] - x[h, i, j, t, d]) \geq 1 \tag{5}$$

$$f[h, i, j] - s[h, i, j] \leq D''[h, i, j] \tag{6}$$

The internal precedences ensure that the predecessor activity and the successor activity are executed in a given order equation (7a). In the same way, the external precedence means that a purchase activity cannot be started until its sale activity has been finished equation (7b).

$$f[h, i, j''] - s[h, i, j'] \geq D[h, i, j', j''] \tag{7a}$$

$$f[h'', i'', j''] - s[h', i', j'] \geq D[h', i', j', h'', i'', j''] \tag{7b}$$

In every schedule period $[t] = T', \ldots, T'' - 1$, the usage of a renewable resource is constrained by its periodic availability and allocations in that schedule period equation (8).

$$\sum_i \sum_j r[h,i,j,k,t] - \mathrm{R}[h,k,t] \leq 0 \tag{8}$$

In every schedule period $[t] = T', \ldots, T''$, the consumption of a non-renewable resource or product is constrained by its initial availability and allocations in and before that schedule period equation (9).

$$\sum_i \sum_j \sum_{t'=T',\ldots,t} r[h,i,j,k,t'] - R[h,k] \leq 0 \tag{9}$$

Soft constraints

Time bounds are constraints that can be violated. There is the lower time bound equation (10) and the upper time bound equation (11).

$$T'[h,i,j] - s[h,i,j] \leq v'[h,i,j] \tag{10}$$

$$f[h,i,j] - T''[h,i,j] \leq v''[h,i,j] \tag{11}$$

Objectives

The objective is to minimise constraint violations of the lower time bounds equation (12) and the upper time bounds equation (13) to reach a feasible schedule. For a feasible schedule, these objectives reach their minimum value if no time bounds are violated, i.e. the value of the objectives is zero.

$$\sum_h \sum_i \sum_j v'[h,i,j] \tag{12}$$

$$\sum_h \sum_i \sum_j v''[h,i,j] \tag{13}$$

Method

Simulation

Simulation is the oldest approach for scheduling. It is still very important today. Simulation progresses either forward or backward. The forward approach simulates the activities working forward in time, whereas the backward approach simulates them backward in time. Simulation-based scheduling is made up of two components, a simulation scheme and a priority rule. There are two simulation schemes that generate a feasible schedule, in most of the cases by extending a partial schedule stage by stage. Once an activity has been scheduled, it is never rescheduled. At each stage, the simulation schemes form the set of schedulable activities from the set of unscheduled activities. Specific priority rules are employed to choose zero or more activities from this set, which are then scheduled and put into the set of scheduled activities. These are the serial method and the parallel method (Kelley, 1963):

- Serial forward (backward) simulation is event-driven. It consists of M stages, where M is the number of activities to be scheduled. At each stage, one activity is selected according to a priority rule and scheduled at the earliest (latest) time taking into account the lower (upper) time bounds, precedences, and resource constraints.
- Parallel forward (backward) simulation is time-driven. It consists of N stages, where N is the number of schedule periods. At each stage, zero or more activities are scheduled so that each stage n is associated with a schedule period $t[n]$ satisfying $t[n] \leq t[n^0]$ ($t[n^0] \leq t[n]$) for every stage $n < n^0$. An activity is selected according to a priority rule and scheduled to start (finish) at the schedule period $t[n]$ considering the lower (upper) time bounds, precedences, and resource constraints.

Alvarez-Valdes and Tamrit (1989) have reviewed a number of priority rules applied to RCPSP. They have listed four kinds of priority rules. Activity-based rules rank the activities according to some attribute that is internal to the activity. Network-based rules rank activities according to some measure of the activity with the rest of the activity network, and CPM-based rules according to measures obtained from the critical path calculation of the activity network with the unconstrained resources. Resource-based rules focus on resource allocations and availability rather that activities and precedences.

Distributed simulation

Distributed simulation (Duffie and Prabhu, 1994; Tirpak *et al.*, 1992) has been proposed as a schedule evaluation method for distributed scheduling, although simulation as an evaluation tool is not specifically aimed at distributed environments. The purpose of the simulations has been to compare several schedule candidates and indicate the most promising one, or only to verify the feasibility of a schedule. It has also been proposed for use in planning for contingencies, and used where the result of scheduling is a priority rule instead of a schedule. Arora and Sachdeva (1989) present how to simulate RCPSP on a distributed system. This requires dividing the project into independent subprojects allocated to independent systems connected through communication channels without shared variables. They propose that parallelism can reduce the computational time needed in the simulation.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

When comparing distributed simulation to contract net and distributed constraint satisfaction, it can be stated that distributed simulation is promising for distributed supply chain scheduling because there are certain problems with other distributed approaches (Seilonen, 1997). Contract net is myopic and deals poorly with precedences, whereas distributed constraint satisfaction is complex and may be trapped into infinite loops or deadlocks. Although distributed simulation does not necessarily optimise the schedules (Davis and Patterson, 1975), it can often find a feasible schedule.

Distributed parallel forward simulation

The parallel method was chosen for distributed simulation because it has been more common than the serial method with RCPSP (Alvarez-Valdes and Tamrit, 1989). Distributed parallel forward simulation is triggered by an application in a company, where a change happens in the resource allocation. The schedule horizon $[t] = T', \ldots, T''$ is divided into the simulation horizons, which have the length $\Delta T \in [1, T'' - T' + 1]$. The first phase is starting. The application communicates with an agent of the same company, and the agent creates a thread, which is concurrent execution in a program. This thread is the root of the simulation. In this phase, it is an inquirer for communicating with agents of the partners, which make their threads to be respondents. In the following phases, the thread of the company is a parent and the threads of its partners are children. The expansion continues to the agents of the partners of these partners and so on, until the simulation span $L \geq 0$, which is the number of the parents in between the thread and application, has been reached. Now, each thread has only one parent. When the expansion reaches the maximum length, the thread has no children. This phase is completed when all the threads have communicated with the agents of their partners to know which partners are involved in the simulation.

The next phase is simulation, which is repeated by each thread involved in the simulation at most $(T'' - T' + 1)/\Delta T$ times. The synchronisation is centralised so that the root starts and finishes the simulation phase, and each parent synchronises its children. The phase of the simulation horizon $[t] = T^0, \ldots, \min\{T^0 + \Delta T - 1, T''\}$ starts from $T^0 \geq T'$ when the thread receives a request message from its parent and sends this message to its children, if it has any. After this, the thread receives messages about purchase orders from its suppliers, updates them to be scheduled, schedules the orders for the simulation horizon using parallel forward simulation, and sends the messages about ready sale orders to its customers. The orders of those partners not involved in the simulation consist of fixed activities, whereas the other orders can contain unfixed activities. Before parallel simulation, an activity $[h, i, j]$ is fixed using the prevailing schedule if there holds $T'[h, i, j] < T'$ or $T''[h, i, j] > T''$. In addition, if there holds $T''[h, i, j] < T' + \Delta T$ or a sale activity $[h', i', j']$ is fixed for an external precedence $[h', i', j', h, i, j]$ or there holds $T''[h'', i'', j''] < T' + \Delta \mathrm{T}$ or a purchase activity $[h'', i'', j'']$ is fixed for an external precedence $[h, i, j, \mathrm{h}'', i'', j'']$, an external activity $[h, i, j]$ is fixed using the prevailing schedule. The simulation phase is completed when the thread receives response messages from its children and sends this message to its parent.

The last phase is finishing. When the thread receives a request message from its parent that the simulation is ready, it sends this message to, and receives response messages from its children. Finally, the agent can extract this thread, and the application gets the information whether the supply chain scheduling was successful or not.

Alvarez-Valdes and Tamrit (1989) have found that the Minimum Slack (MINSLK) rule, which is based on CPM, is the most efficient rule considering due dates. The slack of an activity is the difference between its latest possible starting time and its earliest possible starting time. This rule schedules first the activities with minimum slack because they are the most urgent in the critical paths of the activity networks. MINSLK seems to be suitable for minimising objective (13) after making this rule dynamic and looking ahead. However, if a purchase activity is schedulable, it is always scheduled first. If there holds $T''[h, i, j] \in [T^0 + \Delta T, T^0 + 2 \star \Delta T]$ for a sale activity $[h, i, j]$, the slack is equation (14a) in schedule period $[t]$. Otherwise, this slack is equation (14b).

$$T^0 + \Delta T - D'[h, i, j] - \max\{T'[h, i, j], [t]\} \quad (14a)$$

$$T''[h, i, j] - D'[h, i, j] - \max\{T'[h, i, j], [t]\} \quad (14b)$$

Prototype

Overview

A prototype of the supply chain scheduling system is based on the parallel forward simulation and agent architecture. The prototype tells the application that has triggered supply chain scheduling whether the distributed simulation was successful or not. The component view of the agent architecture describes the three elementary components of the technical implementation of an agent. These components include a communication subsystem, a Data Management

Subsystem, and an application level (Seilonen, 1997). The communication subsystem defines how the units of distribution are connected and how the communication needed for their integration is implemented. The Data Management Subsystem depicts how the various data sections are distributed and how and by what kind of data management systems they are managed. The application level defines the behaviour of the agent and its interconnection mechanisms.

Figure 3 shows the agent architecture of the prototype using OMT. An agent consists of one Manager Thread (Appendix 1) and zero or more Worker Threads (Appendix 2) that implement the application level. The agent is capable of running multiple simulations concurrently and, thus, it has a Worker Thread for each simulation, which has a unique identification of the application that has triggered supply chain scheduling. Each Manager Thread and Worker Thread has one instance of the Data Management Subsystem and Communication Subsystem. The Data Management Subsystem is based on the conceptual model with some extensions that are related the results of the simulation. The Communication Subsystem works out using a certain request-response dialog. This subsystem can send one Message at a time but receive and buffer zero or more Messages. In addition, there is an application to trigger the distributed simulation. This application also employs the Data Management Subsystem and the Communication Subsystem.

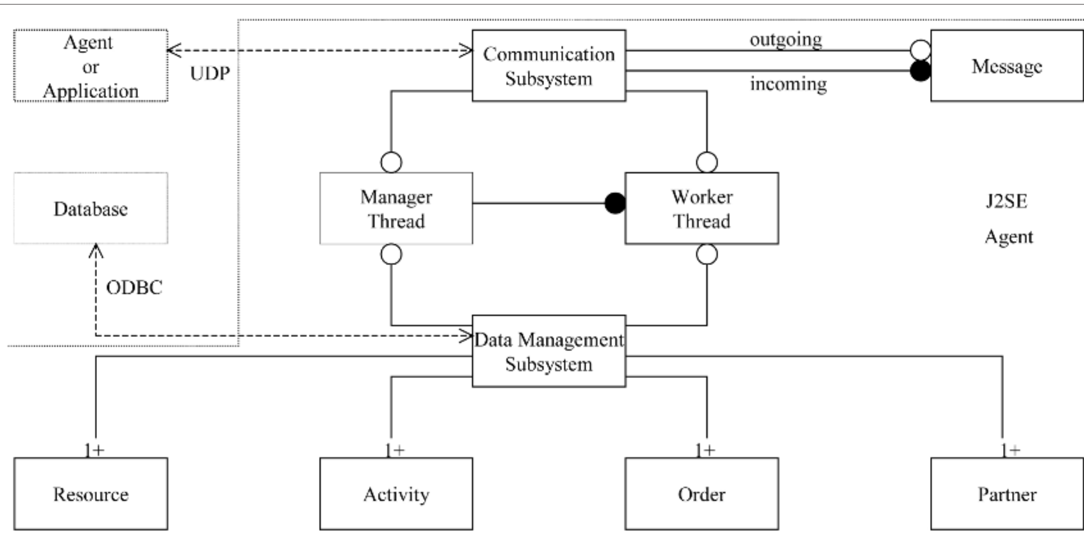
The prototype of the agent has been implemented with Java 2 Platform Standard Edition (J2SE) for programming an agent, User Datagram Protocol (UDP) for communication with an application and other agents, and Open Database Connectivity (ODBC) for data management of a relational database.

Communication subsystem

Figure 4 demonstrates as dialogs how the application and agents communicate using the Communication Subsystem. These dialogs illustrate 16 messages in three communication phases. A Message contains, at least, its type and the addresses of its sender Addr (string) and its receiver that are based on Internet Protocol (IP). The following list presents a sender and a receiver, variables, their type and purpose:

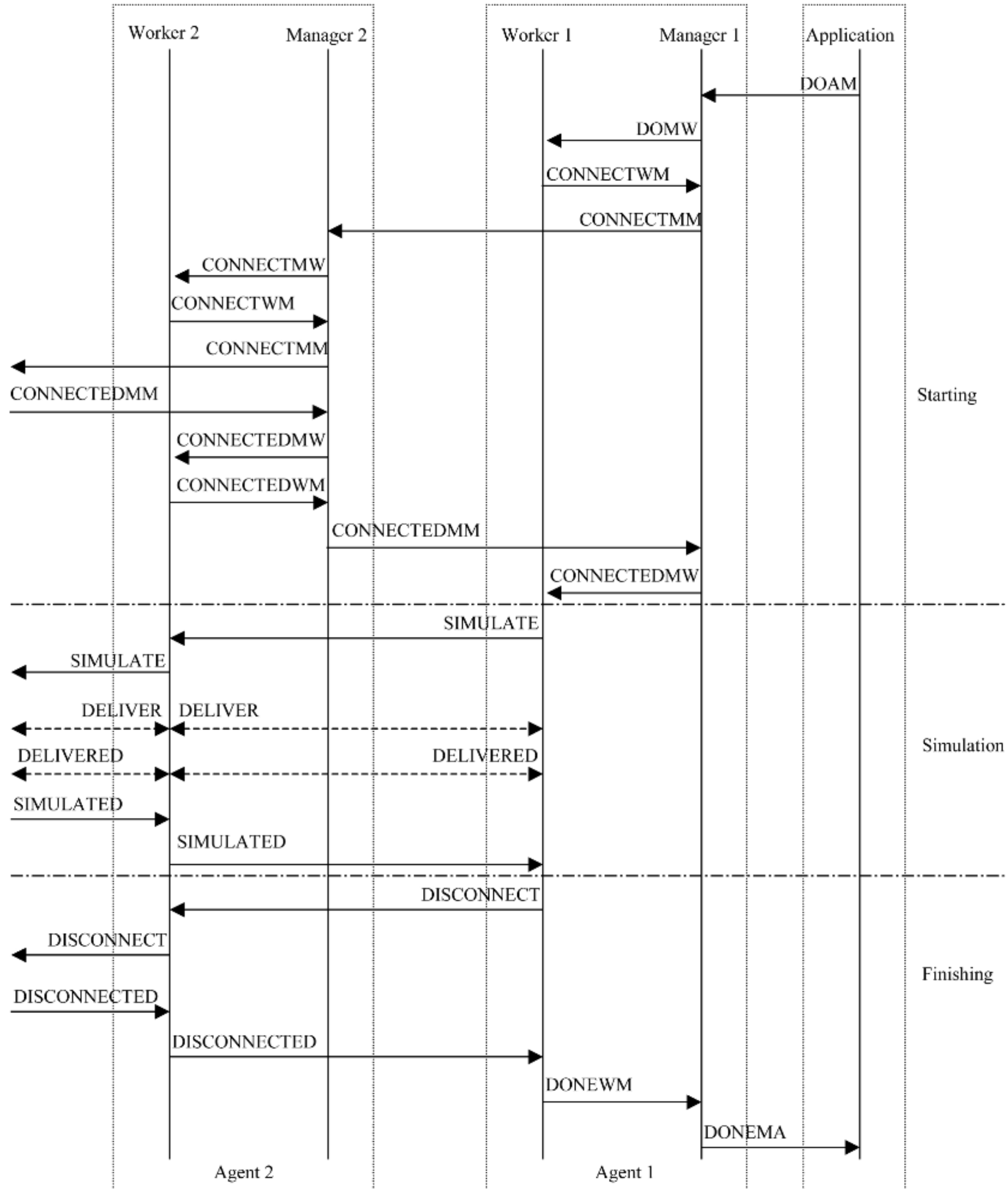
- DOAM (Application – Manager 1): SID (string) the identification of the simulation; Mgr1Addr (string) the address of the Manager 1; L (integer) the remaining simulation span; T' (integer) the first schedule period; T'' (integer) the last schedule period; ΔT (integer) the length of the simulation horizon
- DOMW (Manager 1 – Worker 1 as root): SID; AppAddr (string) the address of the Application; L; T'; T''; ΔT
- CONNECTWM (Worker 1 as inquirer – Manager 1): SID; Mgr2Addr (string) the address of the Manager 2; L; T'; T''; ΔT
- CONNECTMM (Manager 1 – Manager 2): SID; Wkr1Addr (string) the address of the Worker 1; L; T'; T''; ΔT
- CONNECTMW (Manager 2 – Worker 2 as respondent): Mgr1Addr (string) the address of the Manager 1; Wkr1Addr; L; T'; T''; ΔT
- CONNECTEDWM (Worker 2 as respondent – Manager 2): SID; Mgr1Addr; NoParent (boolean) if a respondent has a parent, false, and otherwise true

Figure 3 Agent architecture of the prototype



Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

Figure 4 Communication dialog



- CONNECTEDMM (Manager 2 – Manager 1): SID; Wkr2Addr (string) the address of the Worker 2; NoParent
- CONNECTEDMW (Manager 1 – Worker 1 as inquirer): Mgr2Addr; Wkr2Addr; NoParent
- SIMULATE (Worker as parent – Worker as child)
- DELIVER (Worker as supplier – Worker as customer): OID (string) the identification of the external order; DeliveryTime (integer) when the external order was ready at a supplier including a delay
- DELIVERED (Worker as customer – Worker as supplier): OID; NotLate (boolean) if the external order is late at a customer, false, and otherwise true
- SIMULATED (Worker as child – Worker as parent)
- DISCONNECT (Worker as parent – Worker as child)
- DISCONNECTED (Worker as child – Worker as parent): NoProblem (boolean) if the order was late at a parent or a child, false, and otherwise true

- DONEWM (Worker 1 as root – Manager 1): SID; AppAddr; NoProblem
- DONEMA (Manager 1 – Application): SID; NoProblem

The DO/DONE- and CONNECT/ CONNECTED-dialogs take place through the Managers because of reliability and security reasons. Neither an application and a Worker nor two Workers know each other's addresses beforehand, whereas the Managers do.

The communication subsystem supports two operations. The first operation is Send(addr, msg), where addr is the address of the receiver and msg is the Message to be sent. The second operation is much more complex than the first one because it is employed to synchronise the application, managers and workers using asynchronous messaging. This operation is receive (pairs), which returns the Message, and where pairs is a set of allowable pairs of the sender's address and the type of the message to be received. The second operation has two versions. The version of the application and workers generates an exception after a given time if no message satisfying an allowable pair has been received. This exception inactivates the execution of the Worker.
The version of the managers does not generate exceptions.

Data Management Subsystem
The Data Management Subsystem is based on the conceptual model in Figure 2 but it also contains information that is related to the company, e.g. its prevailing schedule. The Data Management Subsystem stores and maintains information about the environment of the agent, other agents, and the agent itself. It provides an interface to query and update the content of the relational database using Standard Query Language (SQL). The Manager Thread queries the database periodically to ensure it has the most recent information. In comparison, the Worker Thread queries the database before the simulation and updates the database after it has performed the simulation. This update stores information about the activities that have been late in the distributed simulation. An application in a company can utilise this information to show what problems this company has in supply chain scheduling.

Example
The following example illustrates parallel forward simulation in supply chain scheduling. The example covers the partners $[h] \in \{$Supplier, Company, Customer$\}$ for the schedule horizon $[t] = 35, \ldots, 54$ with $\Delta T = 5$ and $L = 1$. Figure 5 shows the activity networks in the example.

All the precedences have no delay, except D[Company, OB2, B21, B22] $= 1$. There also exists D''[Company, OB2, B22] $= 7$. Table I presents the activities and Table II the resources in the example.

Table III illustrates how the distributed forward simulation progresses in this example when the partner (Company) is the root in the distributed simulation, and the parent of children (Supplier) and (Customer). This illustration focuses on the activities to be scheduled, availability of the resources, and messages in the simulation phase. The activities being scheduled and the changes in the resources are expressed in bold.

This example reveals a problem with centralised synchronisation. The partner (Supplier) delivers the external order (OAB) before its release date because it looks ahead one simulation horizon to avoid that this order would be late. However, the external order (OBC) is late and the partner (Company) can achieve nothing by looking ahead because this order has a due date before the next simulation horizon.

Results

The prototype was experimented over an intranet with simple test data covering two-four agents. Since supply chain scheduling requires a lot of information, it is reasonable to concentrate on the most critical activities and resources, as well as on the most important partners. The experiments indicated the feasibility of the chosen model and method in principle, but they also revealed some challenges in practice.

The presented model is most suitable for batch production. It can also be used in one-of-kind production, but external precedences between different companies' internal activities are not possible. Since the model is based on RCPSP that originates from one-of-kind production, it does not support mass production well. Distributed parallel simulation using MINSLK does not always find a feasible schedule, although such a schedule may exist. In the presented model, only optimality means feasibility, but distributed simulation does not necessary find a schedule that violates no time bounds. This is due to the fact that simulation does not guarantee an optimal schedule. One way to diminish the likelihood for this problem is to repeat the distributed simulation using different priority rules. The centralised synchronisation also causes a problem if a sale activity has a release date and its purchase activity has a due date during the same simulation horizon. This problem is less likely when the length of the simulation horizon is shorter, but there is a trade-off that more communication is needed. In addition, a message may sometimes be lost.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

Figure 5 Partners, activities, precedences, resources, and allocations

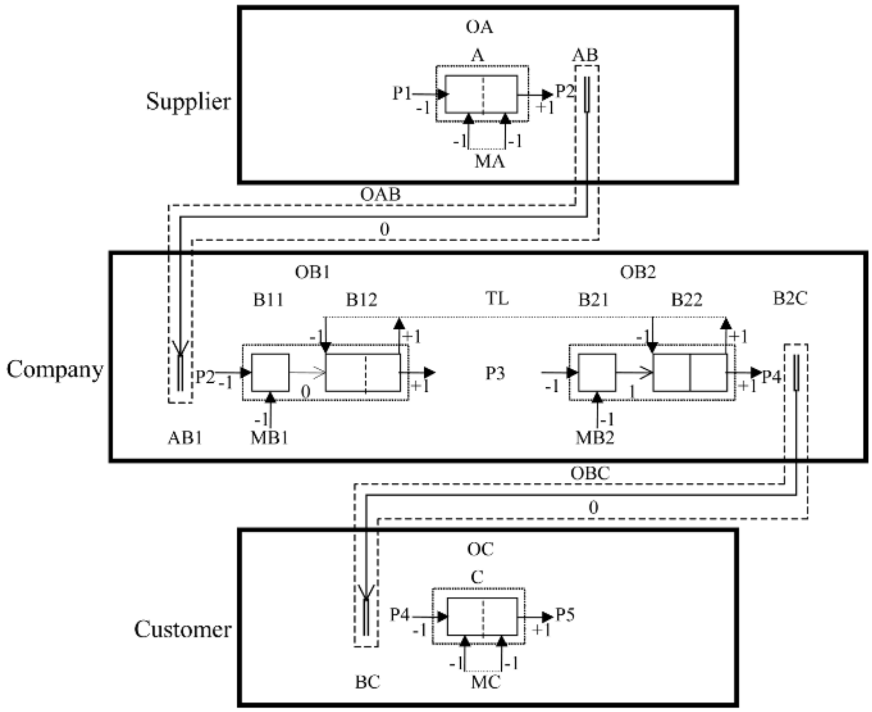


Table I Activities

Partner	Order	Activity	Type	Duration	Release date	Due date
Supplier	OA	A	Non-preemptive	2	35	41
Supplier	OAB	AB	External	0	41	43
Company	OAB	AB1	External	0	41	43
Company	OB1	B11	Non-preemptive	1	40	43
Company	OB1	B12	Non-preemptive	2	41	45
Company	OB2	B21	Non-preemptive	1	40	46
Company	OB2	B22	Preemptive	2	42	49
Company	OBC	B2C	External	0	44	49
Customer	OBC	BC	External	0	44	49
Customer	OC	C	Non-preemptive	2	47	54

Table II Resources

Partner	Resource	Type	Original availability
Supplier	MA	Renewable	1 unit per schedule period
Supplier	P1	Product	1 unit after the schedule period 34
Supplier	P2	Product	Sell 1 unit
Company	MB1	Renewable	1 unit per schedule period
Company	MB2	Renewable	1 unit per schedule period
Company	TL	Non-renewable	1 unit after the schedule period 34
Company	P2	Product	Buy 1 unit
Company	P3	Product	Make 1 unit
Company	P4	Product	Sell 1 unit
Customer	MC	Renewable	1 per schedule period
Customer	P4	Product	Buy 1 unit
Customer	P5	Product	1 unit before the schedule period 55

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

Table III Distributed parallel forward simulation

t	Supplier	*P1*	*MA*	*P2*	Company	*TL*	*MB1*	*P3*	*MB2*	*P4*	Customer	*MC*	*P5*
34		1	1	0		1	1	0	1	0		1	0
		⟵ SIMULATE											
									SIMULATE ⟶				
35	**[OA,A]**	**0**	**0**	0		1	1	0	1	0		1	0
36		0	0	0		1	1	0	1	0		1	0
37		0	**1**	**1**		1	1	0	1	0		1	0
38		0	1	1		1	1	0	1	0		1	0
39	**[OAB,AB]**	0	1	1		1	1	0	1	0		1	0
						⟵ SIMULATED							
	DELIVER(OAB,39) ⟶												
		⟵ DELIVERED(OAB,true)											
		SIMULATED ⟶											
		⟵ SIMULATE											
							SIMULATE ⟶						
40		0	1	1	[OB1,B11] [OB2,B21]	1	1	0	1	0		1	0
41		0	1	**0**	**[OAB,AB1]** **[OB1,B11]** [OB2,B21]	1	**0**	0	1	0		1	0
42		0	1	0	**[OB1,B12]** [OB2,B21]	**0**	**1**	0	1	0		1	0
43		0	1	0	[OB2,B21]	0	1	0	1	0		1	0
44		0	1	0	**[OB2,B21]** [OBC,B2C]	**1**	1	**0**	**0**	0		1	0
		SIMULATED ⟶											
						⟵ SIMULATED							
		⟵ SIMULATE											
									SIMULATE ⟶				
45		0	1	0	[OBC,B2C]	1	1	0	**1**	0		1	0
46		0	1	0	[OB2,B22] 46,47 **[OBC,B2C]**	**0**	1	0	1	0		1	0
47		0	1	0	[OBC,B2C]	0	1	0	1	0	[OC,C]	1	0
48		0	1	0	**[OBC,B2C]**	**1**	1	0	1	**1**	[OC,C]	1	0
49		**0**	**1**	**0**		1	1	0	1	1	[OC,C]	1	0
		SIMULATED ⟶											
						DELIVER(OBC,48) ⟶							
						⟵ DELIVERED(OBC,false)							
						⟵ SIMULATED							
		⟵ SIMULATE											
							SIMULATE ⟶						
50		0	1	0		1	1	0	1	**0**	**[OBC,BC]** **[OC,C]**	**0**	0
51		0	1	0		1	1	0	1	0		0	**0**
52		0	1	0		1	1	0	1	0		**1**	1
53		0	1	0		1	1	0	1	0		1	1
54		0	1	0		1	1	0	1	0		1	1
		SIMULATED ⟶											
						⟵ SIMULATED							
55		0	1	0		1	1	0	1	0		1	1

Although UDP is much easier than Transmission Control Protocol (TCP) to use, it is also unreliable. Taking into account security requirements, TCP with Security Socket Layer (SSL) can provide satisfactory communication.

Conclusions

This paper presents a supply chain scheduling approach especially for those companies that want to be involved in multiple supply chains at the same time. Supply chain scheduling can improve

the company's performance when its activities and resources are costly and sensitive to errors, and its partners require intensive co-ordination. However, the possibility that the competitor may impair this performance through suppliers and customers makes centralised supply chain scheduling unattractive. Distributed supply chain scheduling does not require the company to uncover all information to its partner, but only the information related to the external orders between this company and its partner.

In the literature, Erengüc *et al.* (1999) emphasise the operational aspects of supply chains and suggest the combination of analytical and simulation models to integrate the procurement, production and distribution stages of supply chains, whereas Swaminathan and Tayur (2003) stress real-time decisions and information sharing in supply chains. Duffie and Prabhu (1994), and Tirpak *et al.* (1992) have applied distributed simulation to distributed scheduling in flexible manufacturing systems using the job-shop scheduling problem. Fox *et al.* (2000), Gjerdrum *et al.* (2001), Sadeh *et al.* (2001) and Swaminathan *et al.* (1998) present systems for agent-based supply chain simulation. These systems encompass to some extent scheduling, but they are aimed at modelling and studying the dynamics of the supply chain. Hall and Potts (2003) provide models for scheduling, batching, and delivery problems in supply chains, and dynamic programming methods for scheduling jobs on machines and for forming batches. The literature seems to provide no publications in which distributed simulation has been applied to distributed scheduling using the resource-constrained project scheduling problem in the supply chain context. This paper contributes a supply chain scheduling model that is based on the RCPSP project scheduling problem and a distributed scheduling method that is based on distributed parallel forward simulation. The paper also presents a prototype using an agent architecture implemented with basic Java tools.

Distributed simulation provides a potential approach to distributed supply chain scheduling, but there are many questions. For example, is distributed serial simulation more efficient than distributed parallel simulation? How to synchronise in a distributed way instead of a centralised way? These require further research into supply chain scheduling.

References

Alvarez-Valdes, R. and Tamrit, J.M. (1989), "Heuristic algorithms for resource-constrained project scheduling: a review and an empirical analysis", in Slowinski, R. and Weglarz, J. (Eds), *Advances in Project Scheduling*, Elsevier, Amsterdam, The Netherlands, pp. 113-34.

Arora, R.K. and Sachdeva, R.K. (1989), "Distributed simulation of resource constrained project scheduling", *Computers and Operations Research*, Vol. 16, pp. 295-304.

Blazewicz, J., Lenstra, J.K. and Rinnooy Kan, A.H.G. (1983), "Scheduling subject to resource constraints: classification and complexity", *Discrete Applied Mathematics*, Vol. 5, pp. 11-24.

Chan, F.T., Tang, N.K., Lau, H.C. and Ip, R.W. (2002), "A simulation approach in supply chain management", *Integrated Manufacturing Systems*, Vol. 13, pp. 117-22.

Davis, E.W. and Patterson, J.H. (1975), "A comparison of heuristic and optimum solutions in resource-constrained project scheduling", *Management Science*, Vol. 21, pp. 944-55.

Duffie, N.A. and Prabhu, V.V. (1994), "Real-time distributed scheduling of heterarchical manufacturing systems", *Journal of Manufacturing Systems*, Vol. 13, pp. 94-107.

Erengüc, S.S., Simpson, N.C. and Vakharia, A.J. (1999), "Integrated production/distribution planning in supply chains: an invited review", *European Journal of Operational Research*, Vol. 115, pp. 219-36.

Fox, M.S., Barbuceanu, M. and Teigen, R. (2000), "Agent-oriented supply-chain management", *International Journal of Flexible Manufacturing Systems*, Vol. 12, pp. 165-88.

Gjerdrum, J., Shah, N. and Papageorgiou, L.G. (2001), "A combined optimization and agent-based approach to supply chain modelling and performance assessment", *Production Planning and Control*, Vol. 12, pp. 81-8.

Hall, N.G. and Potts, C.N. (2003), "Supply chain scheduling: batching and delivery", *Operations Research*, Vol. 51, pp. 566-84.

Huang, G.Q., Lau, J.S.K. and Mak, K.L. (2003), "The impacts of sharing production information on supply chain dynamics: a review of the literature", *International Journal of Production Research*, Vol. 41, pp. 1483-517.

Jansson, K., Karvonen, I., Mattila, V.P., Nurmilaakso, J., Ollus, M., Salkari, I., Ali-Yrkkö, J. and Ylä-Anttila, P. (2001), *Uuden tietotekniikan vaikutukset liiketoimintaan (Impacts of Modern Information Technology on Business)*, Teknologiakatsaus (Technology Review) 111, National Technology Agency of Finland, Helsinki.

Kelley, J.E. (1963), "Critical-path method: resources planning and scheduling", in Muth, J.F. and Thompson, G.L. (Eds), *Industrial Scheduling*, Prentice-Hall, Englewood Cliffs, NJ, pp. 347-65.

Little, D., Kenworthy, J., Jarvis, P. and Porter, K. (1995), "Scheduling across the supply chain", *Logistics Information Management*, Vol. 8, pp. 42-8.

Maturana, F.P. and Norrie, D.H. (1997), "Distributed decision-making using the contract net within a mediator architecture", *Decision Support Systems*, Vol. 20, pp. 53-64.

Miyashita, K. (1998), "CAMPS: a constraint-based architecture for multiagent planning and scheduling", *Journal of Intelligent Manufacturing*, Vol. 9, pp. 147-54.

Pritsker, A.B., Watters, L.J. and Wolfe, P.M. (1969), "Multiproject scheduling with limited resources: a zero-one programming approach", *Management Science*, Vol. 16, pp. 93-108.

Sadeh, N.M., Hildum, D.W., Kjenstad, D. and Tseng, A. (2001), "MASCOT: an agent-based architecture for dynamic supply chain creation and coordination in the Internet

economy", *Production Planning & Control*, Vol. 12, pp. 212-23.

Seilonen, I. (1997), *Distributed and Collaborative Production Management Systems in Discrete Part Manufacturing: A Review of Research and Technology*, VTT Research Notes 1837, Technical Research Centre of Finland, Espoo.

Shaw, M.J. (1987), "A distributed scheduling method for computer integrated manufacturing: the use of local area networks in cellular systems", *International Journal of Production Research*, Vol. 25, pp. 1285-303.

Smith, R.G. (1980), "The contract net protocol: high-level communication and control in a distributed problem solver", *IEEE Transactions on Computers*, Vol. C-29, pp. 1104-13.

Swaminathan, J.M., Smith, S.F. and Sadeh, N.M. (1998), "Modeling supply chain dynamics: a multiagent approach", *Decision Sciences*, Vol. 29, pp. 607-32.

Swaminathan, J.M. and Tayur, S.R. (2003), "Models for supply chains in e-business", *Management Science*, Vol. 49, pp. 1387-406.

Sycara, K., Roth, S., Sadeh, N. and Fox, M. (1991), "Distributed constrained heuristic search", *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 21, pp. 1446-61.

Tirpak, T.M., Deligiannis, S.J. and Davis, W.J. (1992), "Real-time scheduling in flexible manufacturing", *Manufacturing Review*, Vol. 5, pp. 193-212.

Yokoo, M., Durfee, E.H., Ishida, T. and Kuwabara, K. (1998), "The distributed constraint satisfaction problem: formalization and algorithms", *IEEE Transactions on Knowledge and Data Engineering*, Vol. 10, pp. 673-85.

Appendix 1: Manager Thread

The Manager Thread has a life cycle that lasts as long as the life cycle of its agent. Its main purpose is to create the Worker Threads for simulations, to connect them, and to destroy those Worker Threads that have become inactive. The following pseudo code describes the behaviour of the Manager Thread:

```
insert information on applications that can be
  involved in simulation into
  Applications
insert information on partners that can be
  involved in simulation into
  OtherManagers
create IP Addr
while true
  receive msg {DOAM from Applications,
    CONNECTWM from OwnWorkers,
    CONNECTMM from OtherManagers,
  CONNECTEDWM from OwnWorkers,
  CONNECTEDMM from
    OtherManagers,DONEWM from
    OwnWorkers}
  remove inactive from OwnWorkers
  if msg is DOAM
      search Worker Thread wkr with
      wkr.SID = msg.SID from
      OwnWorkers
    if wkr was not found
      create Worker Thread wkr;
        wkr.SID = msg.SID
      create IP wkr.Addr;
        wkr.OwnManager = this
      insert wkr into OwnWorkers;
        activate wkr
      send DOMW{msg.SID,msg.Addr,
        msg.L,msg.T′,msg.T″,msg.ΔT}
        to wkr.Addr
  else if msg is CONNECTWM
    send CONNECTMM{msg.SID,msg.
      Addr, msg.L,msg.T′,msg.T″,msg.ΔT}
      to msg.Mgr2Addr
  else if msg is CONNECTMM
      search Worker Thread wkr with
        wkr.SID = msg.SID from
        OwnWorkers
        if msg.L > 0
          if wkr was not found
            create Worker Thread wkr;
              wkr.SID = msg.SID
            create IP wkr.Addr;
              wkr.OwnManager = this
            insert wkr into OwnWorkers;
              activate wkr
        send CONNECTMW{msg.Addr,
          msg.L,msg.T′,msg.T″,msg.ΔT}
          to wkr.Addr
      else if wkr was not found
        send CONNECTEDMM{msg.SID,
          null,true} to msg.Addr
      else
        send CONNECTMW{msg.Addr,
          msg.L,msg.T′,msg.T″,msg.ΔT}
          to wkr.Addr
    else if msg is CONNECTEDWM
      send CONNECTEDMM{msg.SID,
        msg.Addr,msg.NoParent}
        to msg.Mgr1Addr
    else if msg is CONNECTEDMM
      search Worker Thread wkr with
        wkr.SID = msg.SID from
        OwnWorkers
      if wkr was found
        send CONNECTEDMW
        {msg.Addr, msg.Addr,msg.
        NoParent}
        to wkr.Addr
    else if msg is DONEWM
      search Worker Thread wkr with
        wkr.SID = msg.SID from
        OwnWorkers
      if wkr was found and wkr.Root = true
        send DONEMA{msg.SID,
          msg.NoProblem} to
          msg.AppAddr
```

Appendix 2: Worker Thread

The Worker Thread is running until the simulation is finished. On the other hand, if an exception is generated, the Worker Thread becomes inactive. Since Alvarez-Valdes and Tamrit (1989) have described parallel forward simulation, this description focuses on centralised synchronisation. This synchronisation ensures that certain messages are not sent too early and certain messages are received sufficiently long. With regard to this, the following pseudo code describes the behaviour of the Worker Thread:

```
insert information on partners that can be
  involved in simulation into
  OtherManagers
receive msg {DOMW from OwnManager,
  CONNECTMW from OwnManager}
T′ = msg.T′; T″ = msg.T″;ΔT = msg.ΔT;
  NoProblem = true; T = T′
if msg is DOMW TmpAddr = msg.AppAddr;
  L = msg.L; Root = true
else
  TmpAddr = msg.Mgr1Addr;
    L = msg.L − 1; Root = false
  create Partner Parent;
    Parent.Addr = msg.Wkr1Addr
for every ptr in OtherManagers
  send CONNECTWM{SID,ptr.Addr,
    L,T′,T″,ΔT} to OwnManager.Addr
while CONNECTEDMW has not been
  received for all in OtherManagers
  receive msg {CONNECTMW from
    OwnManager, CONNECTEDMW from
      OwnManager}
  if msg is CONNECTMW
    send CONNECTEDWM{SID,
      msg.Mgr1Addr,false} to msg.Addr
  else if msg.Wkr2Addr ≠ null
      create Partner ptr;
        ptr.Addr = msg.Wkr2Addr
      insert ptr into OtherWorkers
      if msg.NoParent = true insert ptr
        into Children
if Root = false
  send CONNECTEDWM{SID,
    TmpAddr,true} to OwnManager.Addr
  while SIMULATE has not been received
    receive msg {CONNECTMW from
      OwnManager,
      SIMULATE from Parent}
    if msg is CONNECTMW
      send CONNECTEDWM{SID,
        msg.Mgr1Addr,false} to msg.Addr
calculate effects of fixed activities on resources
insert fixed activities into Scheduled
insert unfixed internal and sale activities into
  Unscheduled
insert unfixed purchase activities into
  Purchases
while T ≤ T″
  for every ptr in Children send SIMULATE
    to ptr.Addr
  perform parallel simulation from T to
    min{T + ΔT − 1, T″}
  remove all from Sales
  insert sale activities made ready during
    recent simulation horizon into Sales
  for every act in Sales
    search Partner ptr for act.OID from
      OtherWorkers
    send DELIVER{act.OID,
      act.DeliveryTime} to ptr.Addr
  while DELIVERED has not been received
    for all in Sales and
    SIMULATED from all in Children
      receive msg {DELIVER from
        OtherWorkers,
      DELIVERED from OtherWorkers,
        SIMULATED from Children}
    if msg is DELIVER
      NotLate = true
      search External Activity act for
        msg.OID from Purchases
      if act was found
act.DeliveryTime = msg.DeliveryTime
        if act is in late NotLate = false;
          NoProblem = false
        move act from Purchases to
          Unscheduled
        send DELIVERED{msg.OID,
          NotLate} to msg.Addr
    else if msg is DELIVERED and
      msg.NotLate = false
      NoProblem = false
T = T + ΔT
if Root = false
    send SIMULATED to Parent.Addr
    while SIMULATE or DISCONNECT
      has not been received
      if T ≤ T″
        receive msg {DELIVER from
          OtherWorkers,
          SIMULATE from Parent}
      else
        receive msg {DELIVER from
          OtherWorkers,
          DISCONNECT from Parent}
      if msg is DELIVER
        NotLate = true
        search External Activity act for
          msg.OID from Purchases
        if act was found
          act.DeliveryTime =
            msg.DeliveryTime
```

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 756–770

```
                if act is in late NotLate = false;
                   NoProblem = false
                move act from Purchases to
                    Unscheduled
                send DELIVERED{msg.OID,
                   NotLate} to msg.Addr
for every ptr in Children send
   DISCONNECT to ptr.Addr
while DISCONNECTED has not been
   received from all in Children
   receive msg {DISCONNECTED from
   Children}
      if msg.NoProblem = false
          NoProblem = false
if Unscheduled or Purchases is not empty
   NoProblem = false
if Root = false send
   DISCONNECTED{NoProblem} to
   Parent.Addr
else send DONEWM{SID,TmpAddr,
   NoProblem} to OwnManager.Addr
inactivate this
```

A decision support system to facilitate resources allocation: an OLAP-based neural network approach

H.C.W. Lau
A. Ning
W.H. Ip and
K.L. Choy

The authors

H.C.W. Lau, **A. Ning**, **W.H. Ip** and **K.L. Choy** are all based at Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong.

Keywords

Decision support systems, Resource allocation, Neural nets, Artificial intelligence

Abstract

The emergence of advanced information technologies strengthens the capability to the entrepreneur to manage and manipulate data. However, the quality of information, the capability of providing the right information to the right person, and the utilization of information are still in doubt. Therefore, increasing numbers of firms have realized and started to develop as well as improve their existing information systems to fit the ever-changing business needs of the organization to support decision-making for the volatile business environment. Indeed, previous research studies have found that logistics management is the great frontier of cost reduction. Therefore, in this paper, an infrastructure of a decision support system is proposed to capture and maintain the business and resources allocation information with the adoption of the neural network for its artificial intelligent characteristic that mimic the operation of human brain to generate solutions systematically. The proposed system is adopted by a shipping company to assist allocation of containers.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 771–778

DOI 10.1108/17410380410565357

Introduction

Enterprise nowadays is facing global competition; being able to have competitive edge with continual improvement, operate in low cost, and response to customer demands becomes the key of survival. It is especially difficult for companies whose operating costs are relying on high investment in assets; the only way to reduce cost of operation is to reduce complexity of workflow and to utilize the resources within the company.

Tremendous amount of data that are related to business operations and decisions are flooding into business. There is no doubt that data is one of the organization's most valuable resources. However, not many organizations are able to fully utilize their available data to assist decision-making and daily operations, which directly affect the competitiveness in the market. Therefore, it is crucial to be able to generate the right information and deliver the information to the right person at the right time. Indeed, the major activity of business operation lies on the systematic processing of knowledge to create value for customers. The key to build a successful enterprise depends heavily on the agility of the company to face the ever-changing business environment. Evidence to date suggested that extensive delays in the delivery schedule, quality problems, cost overruns, and increasing clams and litigation have caused serious harm to the companies. In order to simplify workflow and utilize the resources in the organization by closing monitor the available resources, the company reengineers the workflow processes and reallocates the available resources. In this paper, a framework of a resources management system is proposed to control resources consumption within organization, which would also affect the workflow processes in a positive way.

Related studies

Number of research studies have been performed to propose an information System framework to manage supply chain network and logistics. However, most of them are focused on information exchange between companies and vendors, and companies and customers, not many of them have proposed any strategically developed system or even addressed the needs in managing the physical segment – transportation management, of supply chain and logistics management.

Received: 27 June 2003
Accepted: 17 February 2004

Wan and Levary (1995) had proposed a linear programming transportation model to allow the shippers to evaluate all possible means of obtaining the lowest price for a given shipping route in a short period of time. The model described in the study incorporates linear programming into price negotiation process for contracting shipping companies. However, it was lack of flexibility to allow management to make decisions for tackling unpredicted problems and generate strategic offers to meet the market needs. In other words, the proposed model did not allow the management to manipulate with the data to satisfy his/her desires. On the other hand, Mason *et al.* (2003) have simulated an integration of warehouse management systems what contain information on supplier/customer warehouse inventory levels and key customer order patterns. In the study, it found that the integrated paradigm improved customer service through improved efficiencies, reduced costs, reduced lead-time variability. Moreover, Shen and Khoong (1995) have proposed a decision support system that is embedded with optimization model to solve the problems concerning the distribution of empty containers for a shipping company. The optimization model deployed in the decision support system was able to solve the problems for land transportation systems, however, it required further development to carry out processes for land and sea systems. Furthermore, the proposed system did not include techniques such as artificial intelligence and forecasting.

Stopford (2002) analyzed and addressed the opportunities and threats to the commercial organization of shipping by the e-commerce revolution, and the impacts of the different information technologies on the shipping industry from a management prospective. The author suggested five benefits of Web communications:

(1) compatibility – Web browser provides a common platform for system development;
(2) convenience – demand driven access to information that allows user to obtain information as he/she needs;
(3) simplicity – the learning curve is short and it is easy for user to post, view, change, and obtain information;
(4) integration – systems developed independently can be integrated to a standardized platform (Web browser) easily; and
(5) affordability – Web systems are more economical to be developed than other communication systems (Stopford, 2002).

However, the author was not able to suggest the use of artificial intelligence and other advanced technologies with the advantageous use of Web systems that are beneficial to shipping industry.

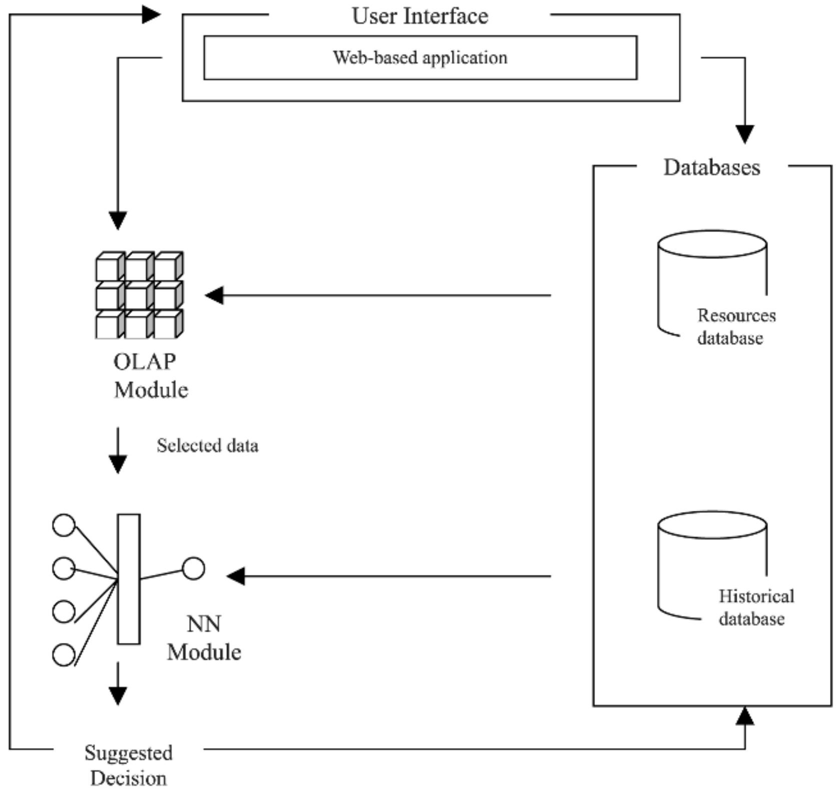
The recent trend of global manufacturing is to implement system infrastructure that allows analysis being performed on vastly distributed data according to the elements of business strategies. In the era of information-based management, the key of success is to recognize the company's competitive advantages and weaknesses with the support of information technologies for decision-making (Porter and Millar, 1988). Therefore, we propose to use online analytical processing (OLAP) as a tool for knowledge discovery with the support of neural network to generate an informed solution.

Proposed framework of resources management system

The proposed resources management system consists of three main modules: user interface, databases, and OLAP-based neural network module. The user interface is a Web-based application that enables user to access the system and submit information to the system anywhere at anytime. The databases, on the other hand, maintain and acquire the data that are generated in the transactions processes and other workflow processes. It also ensures, all the valuable data are accessible for the management to make decisions. Lastly, the OLAP-based neural network module is considered the brain of the resources management system (Figure 1).

The brain of the decision support system for resources allocations is the OLAP-based neural network module that is capable to analyze tremendous information that is pouring into the company through different medium. The main purpose of adopting OLAP is to analyze the aggregate data with multidimensional view. It collects distributed data while performing as a single information source. OLAP tool assists the decision-maker to create appropriate knowledge and analysis models by browsing the appropriate data groups, and defining the model relations between them (Datta and Thomas, 1999). In early 1990s, technological advances in data modeling, databases, and application developments made it feasible for decision-makers to analyze data with a common data source. According to the definition of OLAP Council, OLAP is a "category of software technology that enables analysts, managers and executives to gain insight into data through fast, consistent, interactive access to a wide variety of possible views of information that has been transformed from raw data to reflect the real dimensionality of the enterprise as understood

Figure 1 Resources management system infrastructure



by the user (Inmon, 1992)". In other words, OLAP converts data into useful information by transforming raw data to meaningful and organized information with its analysis features so that it reflects the real dimensionality of the enterprise that is understandable by user. Most importantly, OLAP has the ability to provide managers with information they need to make effective decisions about an organization's strategic directions. Devlin summarized the direction of information-based management as: single information source, distributed information availability, information in a business context, automated information delivery, and information quality and ownership (Delvin, 1997).

However, OLAP has its own drawbacks. Whilst OLAP is able to provide numerical and statistical analysis of data in an efficient and timely manner, it lacks the intelligent element to provide predictive advice. For example, it is unable to project possible outcomes based on the historical records and it cannot provide recommendations with previously recorded cases. In this respect, it is necessary to find an approach to cope with its pitfalls in order to form a complete system. Neural network is chosen to be the complement of OLAP since one of the objectives of the system is that it should generate suggestions that are as good as or even better than the decision made by the expert, provided that the same set of input data are given. The learning process of human is through a repetitive learning cycles which is similar to the learning process of neural network. Therefore, the neural network is selected to be part of the hybrid system to take advantage of its capability to operate with incomplete data to generalize, abstract, and reveal insight (Wasserman, 1989; Sharda, 1994; Kasabov, 1999). Neural network is statistically oriented tool that excels at using data to classify cases into categories (Davenport and Prusak, 2000). Neural networks "learn" patterns from data directly by examining the data repeatedly, searching for relationships, automatically building models, correcting over and over again the model's own mistake (Datta and Thomas, 1999). In other words, like other simulation models, neural network substitutes the real system in predicting and controlling system responses for the purpose of dynamic control (Haykin, 1994). These characteristics of neural network assist decision-making for resources allocation, since resources are often limited and the resources must be used in the operations of the corporation that are beneficial to the overall performance of the company.

The resources data and information are enshrined in the OLAP system to take the advantages of its provision of multi-dimensional

views on the scattered data and generation of aggregated data. The resources database provides the necessary data input for OLAP system. The resources database includes the assets information, usage constraints, and the policy of the company regarding the use of the resources. The in-depth data that are generated by the drill function of OLAP system would be submitted to the neural network system for analysis and a proposed solution will be generated based on categorizing a multi-dimensional input vector. The suggested solutions are provided to the user through the Web-based user interface.

Case study

Background

Victory Shipping Co. Ltd is a medium size shipping company that provides shipping and handling services from Europe to Pacific Rim. Owing to the intense competition in the market, Victory Shipping Co. has to stay low cost in operation by reducing cost in managing containers, which are the biggest assets as well as costs of the company. In order to reduce the burden of investment, Victory Shipping Co. has been actively engaged in the use of free one-way lease offer by the container manufacturers in China. The container manufacturers in China are willing to offer free one-way lease to shipping companies to take advantage of the free charge of delivery of container to the buyers in Europe. The container manufacturers instead of chartering vessel to reposition the new containers to European buyers, they would offer the shipping company 60 days free-of-charge usage, and the shipping company must deliver the containers to the designated depots in Europe within the free-of-charge period. However, if the shipping company cannot deliver the containers on time, a high rental fee will be charged to the shipping company.

After the containers have arrived their destination, besides the free one-way lease containers, Victory Shipping Co. would have to make decision about the containers, such as re-use its self-owned containers, refurbish its containers, or phase out the leased containers to the container leasing companies. Victory regional offices are responsible to prepare instructions regarding the usage of the containers and the agent at the depot would know what to do with the units after the arrival of the containers.

Existing practice

Container Control Department in the head office of Victory Shipping Co. controls all the contracts with leasing companies and container manufacturers. The manager of the Container Control Department decides the procedures for controlling the container fleet, phasing out the units, or delivering the one-way leased unit to the container owner. The manager would inform the operators and the regional managers through the e-mailing system regarding the instructions. Operators would extract a complete on-board list in MS Excel format of the particular vessel, and type in the disposal instructions for each unit manually. After the instructions are added to the MS Excel file, the file would be sent to the agents of the destinations through e-mail.

After analyzing the workflow operations of Victory Shipping Co., number of problems are found. Firstly, problems of the existing practice are that most of the disposal instruction files are distributed through e-mail, which is quite difficult to keep track of the status as the files may be updated without acknowledging all the associated personnel. Secondly, there is lack of a systematic way to keep track of the records of each container, which creates problems to the manager to obtain the information for decision-making regarding refurbishment and disposal of container. Thirdly, since the disposal instructions are input manually, there are possible human errors, which would create financial loss to the company if the containers were not delivered on time to the container buyer. Fourthly, it commonly requires at least 30 minutes time to prepare one disposal instruction even for the experienced operator. Moreover, the right personnel are necessary to be recruited as the operator, since the operator would need to have the knowledge on the leasing contracts. For example, if the destination does not allow re-using the one-way leased container, the operator must give proper advise to the manager when he/she sees there is violation to the leasing contracts. Furthermore, the change of the inter-ports activities are usually not recorded to the on-board list, which has often created problems in controlling the one-way unit and the possibility that Victory Shipping Co. failed the one-way leasing commitment and ends up paying high cost for late delivery of the container to the container buyer. Lastly, the activities are not recorded properly and the containers could not be fully utilized by planning the routes.

The management of Victory Shipping Co. realized the need to strengthen the control of the container, especially the one-way leasing containers, which often incur high costs to the company due to delay of delivery to the destination accordingly. Also, there are needs in expanding the services and one-way leasing activities for different vessels. The management of Victory Shipping Co. has decided to develop a resources allocation and

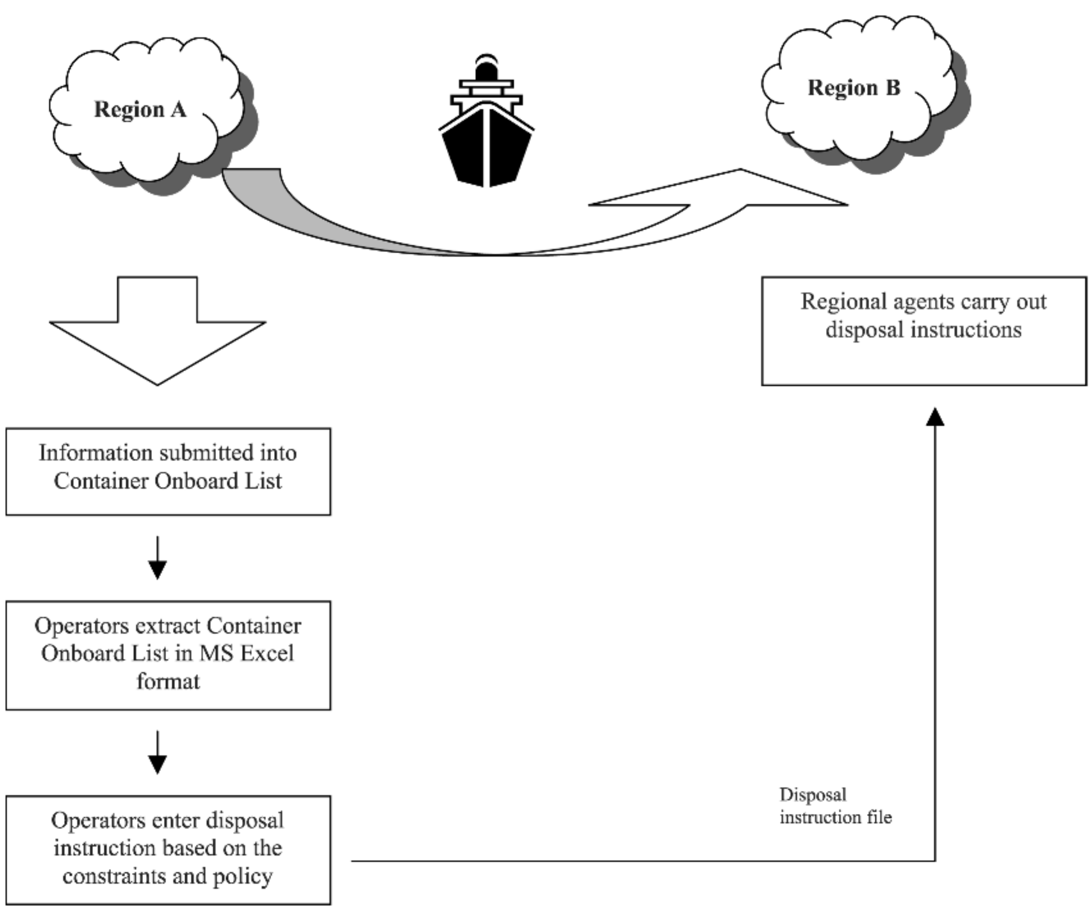
management system to assist decision-making and generates reliable disposal instructions for the regional managers and agents (Figure 2).

Adoption of proposed resources management system

An online decision support system was developed to facilitate the control of containers for Victory Shipping Co. Managers can obtain the information needed through the Internet by submitting the inquiries and instructions to the system. Since the system is connected to the corporate database, managers can find the information regarding the leasing contracts, container type, container status, destination, customers, vendors, etc. through the system. On the other hand, the system allows the agents extracting the on-board disposal instruction from the resources management system and distributes the disposal instruction through the system to the regional managers and agents. The regional managers and agents are also responsible to submit information of the containers which leave and arrive the port to ensure the inter-ports activities are recorded and updated (Figure 3).

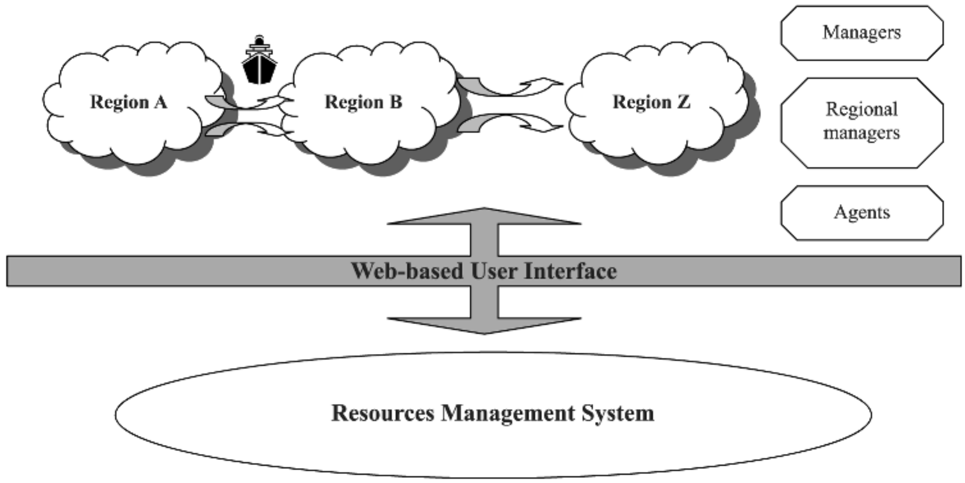
A resource management system includes an OLAP module is built with Web-based application, which ensures the system is accessible through the Internet. The data enshrine in the system repository are transmitted to OLAP, which captures all the necessary information for manipulation to take advantage of its provision of multi-dimensional views on the scattered data and generation of aggregated data. For Victory Shipping Co., the information regarding the usage of the containers, leasing contracts information, container on-board lists, customer information, vessels, etc. are captured in the multidimensional data structure that allows the managers to drill for information. The neural network, which is linked to the OLAP system, would generate suggested routes that fully utilize the containers to avoid paying any extra rental costs for the one-way leasing containers and extra delivery costs to the repair shop for the containers that need refurbishment. The suggested routes are provided to the managers who would make the final decision of the disposal instructions for the containers. The disposal instructions are then made available on the Internet and distributed to the associated

Figure 2 Existing practice of Victory Shipping Co.



Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 771–778

Figure 3 Flows of information with the new system in Victory Shipping Co.



personnel who can then plan ahead for the regional activities (Figure 4).

Victory Shipping Co. has deployed the proposed resources management system in numbers of vessels and locations before full implementation of the system in the company. The company has selected the Asia vessel, which includes the ports in Singapore, Hong Kong, Shanghai, etc., and the Europe vessel, which includes the ports in Hamburg, Southampton, Rotterdam, etc. The resources management system has installed in the corporate Intranet for testing.

Managers in the headquarters, which is located in Hong Kong, plan the routes for a shipment after it has left from the port in Shanghai, and compared the routes of the containers suggested by the resources management system. The managers found that the suggestion generated by the system has approximately 90 percent of the routes and ports that are similar to the one the manager planned, and all of the routes that are suggested by the system are able to deliver the containers to the container buyer on time. However, the managers are still concerned regarding the utilization of the containers according to the system suggested routes. Since the suggested routes are bounded strictly by the contract dates, the system lacks the capability to compare the benefits and costs of the usage of a container. However, the intelligence of the system can be improved by training the neural network with an additional set of data of the costs and benefits of using a contract-expired container.

Furthermore, managers found that the OLAP system enables them to obtain the in-depth information regarding the usage of the company-owned containers and the leasing containers. Indeed, the managers find out by the OLAP system that some of the containers are empty or not fully occupied but are placed on-board, instead of waiting for the next shipment (Table I). Also, the managers found that the empty containers are not due for the one-way leasing contract nor require any refurbishment yet for the next destination. In other words, the empty containers should be reused and wait for the next shipment in order to fully utilize the containers before the end of the contract or repair period. There are surely wastes of the limited resources. Furthermore, the OLAP system allows the company to monitor regional performance by generating an on-land disposal instruction report to see if the instructions have been completed on time.

Evaluation of the proposed resources management system

By adopting the resources management system, Victory Shipping Co. is able to benefit in number of ways. Firstly, Victory Shipping Co. can reduce the labor costs for administration operations, which was meant to provide the information to support decision-making, as the managers are able to access the information through resources management system that also generates suggestions for the managers to utilize the limited resources and exploit opportunities. As mentioned above, the managers in the Victory Shipping Co. are able to monitor the regional performance closely with the assistance of OLAP system, managers can expand or even shrink the services depending on the needs of the region. Furthermore, resources management system helps in minimizing the delay of instructions distribution within the company. The information regarding the shipment, containers, etc., all the information

Figure 4 New practice of Victory Shipping Co. after adoption of resources management system

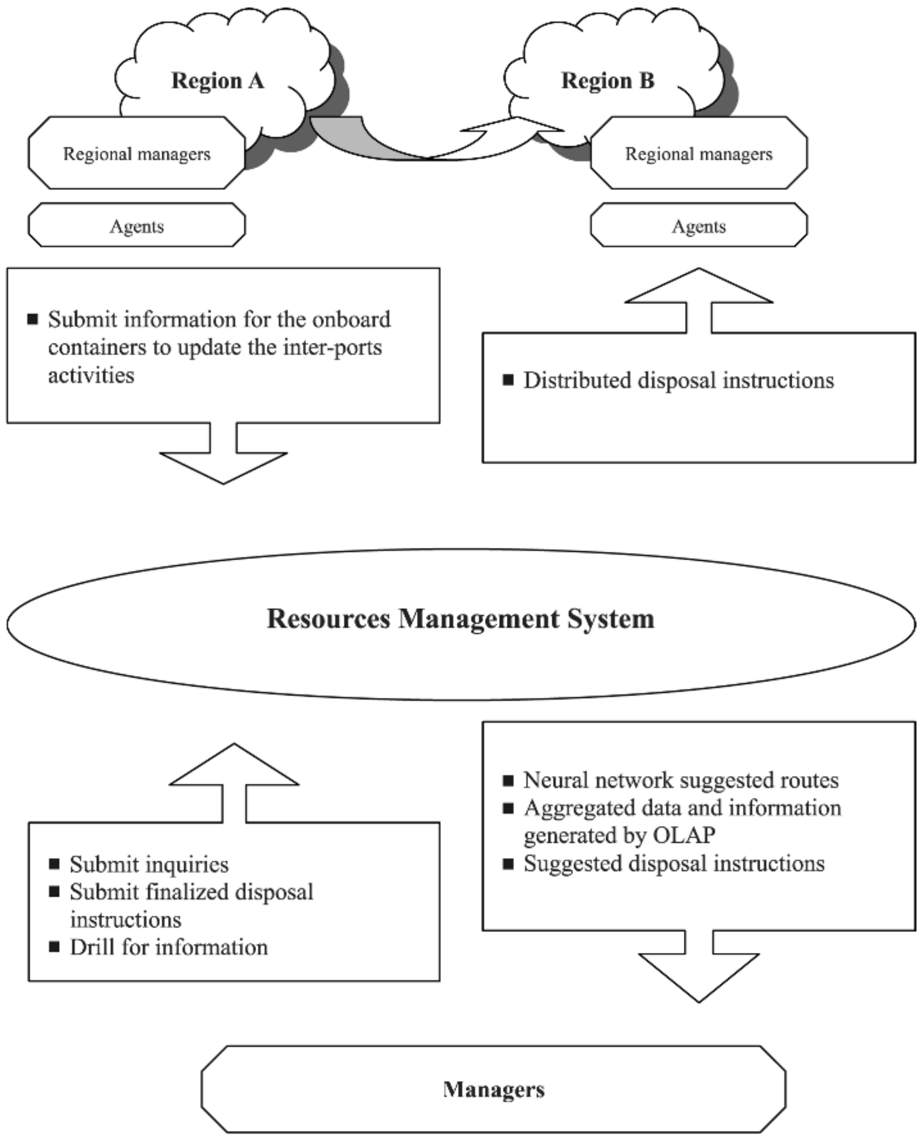


Table I OLAP output table

CTR_no	CTR_type	Owner	Status	Date	Destination	Disposal remark
AMZU8370509	45G1	O	Empty on-board	22 February 2002	YANTIAN	CSV03
AMZU8386547	45G1	O	Empty on-board	22 February 2002	YANTIAN	CSV02
BOXU2215581	22G1	S	Empty on-board	22 February 2002	YANTIAN	
CAXU2043601	22G1	M	Empty on-board	17 February 2002	NINGBO	
CAXU2185360	22G1	M	Empty on-board	22 February 2002	YANTIAN	
CAXU2192035	22G1	M	Empty on-board	22 February 2002	YANTIAN	
CAXU2340976	22G1	O	Empty on-board	17 February 2002	NINGBO	
CAXU2562000	22G1	M	Empty on-board	17 February 2002	NINGBO	
CAXU2575754	22G1		Empty on-board	17 February 2002	NINGBO	
CAXU2994874	22G1	M	Empty on-board	22 February 2002	YANTIAN	
CAXU4106139	42G1	M	Empty on-board	22 February 2002	YANTIAN	
CAXU4363918	42G1	M	Empty on-board	22 February 2002	SHANGHAI	
CLHU2145807	22G1	M	Empty on-board	17 February 2002	NINGBO	

Notes: CSV03 YANTIAN: reuse unit to Los Angeles; CSV02 YANTIAN: reuse unit to Genoa, Venice

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 771–778

that are necessary for decision-making and carrying out instructions, are available through a Web-based Resources Management System that is accessible anywhere at anytime. Also, the agents are able to obtain the most updated disposal instructions through the system. Different time zone and the occurrences of national holidays will no longer be a barrier of communication in the company anymore. Moreover, the disposal instructions are not input and filtered manually anymore, the accuracy of data improves significantly.

However, intensive training is needed to equip the managers with the knowledge of using the resources management system. Especially for the OLAP application, which has an interface that allows the user to drill down for information by combining the data in multi-dimensional manner. The user may find it difficult to visualize their needs and express their needs by manipulating the data with an OLAP application. Moreover, one of the main benefits of the resources management system is that it is accessible through the Internet. In other words, the Internet connections are critical to the capability of the system. However, the Internet infrastructure of some developing countries is not so sophisticated, which creates problems for the regional managers and agents to access the information.

Conclusion

Economic organizations always devote their full efforts to obtain the best available information in order to make informative decisions. The proposed infrastructure of decision support system allows the user to obtain the information that are necessary for decision-making while enables to exploit opportunities with the existing information. Further development of a decision support system that links with the supplier and customer by enabling them to logon to the company portal to access the information they need for business operations.

References

Datta, A. and Thomas, H. (1999), "The cube data model: a conceptual model and algebra for online analytical processing in data warehouses", *Decision Support Systems*, Vol. 27 No. 3, pp. 289-301.

Davenport, T.H. and Prusak, L. (2000), *Working Knowledge*, Harvard Business School Press, Boston, MA.

Delvin, B. (1997), *Data Warehouse: From Architecture to Implementation*, Addison-Wesley, Reading, MA.

Haykin, S. (1994), *Neural Networks, a Comprehensive Foundation*, Macmillan, New York, NY.

Inmon, W.H. (1992), "Data warehouse – a perspective of data over time", *Database Management*, February.

Kasabov, N.K. (1999), *Foundations of Neural Networks, Fuzzy Systems, and Knowledge Engineering*, NetLibrary Inc., Boulder, CO.

Mason, S.J., Ribera, P.M., Farris, J.A. and Kirk, R.G. (2003), "Integrating the warehousing and transportation functions of the supply chain", *Transportation Research Part E.*, Vol. 39, pp. 141-59.

Porter, M.E. and Millar, V.E. (1988), "How information gives you competitive advantage", The Best of Harvard Business Review, *Harvard Business Review*, pp. 227-40.

Sharda, R. (1994), "Neural networks for the MS/OR analyst: an application biography", *Interfaces*, Vol. 24 No. 2, pp. 116-30.

Shen, W.S. and Khoong, C.M. (1995), "A DSS for empty container distribution planning", *Decision Support Systems*, Vol. 15, pp. 75-82.

Stopford, M. (2002), "E-commerce-impliccations, opportunities, and threats for the shipping business", *International Journal of Transport Management*, Vol. 1, pp. 55-67.

Wan, K. and Levary, R.R. (1995), "A Linear-programming-based price negotiation procedure for contracting shipping companies", *Transportation Research Part A*, Vol. 29A No. 3, pp. 173-86.

Wasserman, P.D. (1989), *Neural Computing Theory and Practice*, Van Nostrand Reinhold, New York, NY.

An object-based relational data base system using re-configurable finance and material objects

W.H. Ip
Bocheng Chen
Henry Lau and
Wangqi Sunjing

The authors

W.H. Ip and **Henry Lau** are both based in the Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, People's Republic of China.
Bocheng Chen and **Wangqi Sunjing** are both based at the School of Economics & Management, Tsinghua University, Beijing, People's Republic of China.

Keywords

Logistics, Resource allocation, Databases, Manufacturing resource planning

Abstract

Any manufacturing information system today must be able to both "reconfigure" and "reengineer" operations in a cost-effective way. The objective of this paper is to propose an enterprise resource planning (ERP) system based on the re-configurable characteristics of material objects (MO) and finance objects (FO). The implementation of this information system is based on the object technologsy concept, which composes enterprise applications in reusable software components made up of relevant manufacturing data. By analyzing the factors and the methods of integration of MO and FO, it can be shown that the proposed approach is more appropriate for the design and implementation of an ERP system, and that it is particularly suitable for small and medium-sized enterprises (SMEs). The results demonstrate a flattened organizational structure, better communication, and enhanced workflow reconfiguration.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 779–786

DOI 10.1108/17410380410565366

1. Introduction and related research

Recently, in China, the concept and application of electronic commerce has become very popular; as a result, more and more enterprises are recognizing the importance of information management in their enterprises. There is a variety of ERP software available on the market but SMEs in China very often cannot benefit from it because of the high costs of customization and software maintenance. These companies, which normally have tight budgetary constraints, find it difficult to justify the purchase and application of ERP. A more effective and simplified ERP software that is affordable and easy to customize is needed. This would enable SMEs to modify and change their workflows to meet their information needs.

On the other hand, the demand for flexibility of manufacturing information systems to provide a fast response to market demands is increasing rapidly. A number of tools and software application solutions have been built for manufacturers to use in order to improve enterprise operations in a cost-effective way. ERP/MRP-II and CAD/CAM packages are only a few of these products. There have been various research papers on MRP/ERP and its relationships with business processes re-engineering (Gartner Group, 1990; Hammer, 1990; Davenport and Short, 1990). Li and Williams (2000), and Chen and Vallespir (1997) proposed the design of enterprise architectures using the Purdue and GRAI models. They analyzed the design of a large-scale enterprise model, but their principles are quite different from the concerns of ERP practitioners (Gartner Group, 1990). Ng *et al.* (1999) and Ng and Ip (1998) have put forward a large-scale integrated ERP model, but it is not intended for SME applications. In recent years, the concept of object-oriented and component-based development techniques (Rumbaugh *et al.*, 1991; Booch, 1996) has been embraced to create a number of applications in various fields. Packages such as Paradigm Plus (Paradigm, 1998), ActiveX components (Microsoft Corporation 2000a, b, c), and COBRA (Object Management Group 1998) are some of the popular ones. Greenbaum (1993), Unisys and SAP (1998), and SAP company (1999) have worked together to develop an integrated package called Enterprise Application Solutions for information communication among various business operations within a company.
These companies have basically developed a total

Received: 30 June 2003
Accepted: 14 May 2004
The authors would like to acknowledge the work was partly supported by the National Natural Science Foundation of China (70231010).

system solution that includes software applications, computers and networking facilities for customers, all integrated seamlessly to facilitate the data transfer of the organization. Though the concept and their methodologies can be traced back to 1990, a simplified, re-configurable approach to the ERP process suitable for SMEs and their analyses is not available.

The long-term significance of this research is its impact on the approach based on which manufacturing enterprises and in particular SMEs deal with manufacturing information systems. A component-based approach to ERP is introduced, which can significantly change both the way companies develop their information applications and their perceptions of these applications. More importantly, a methodology of a generic nature is demonstrated, exemplified by an application in SMEs; this can be implemented according to an enterprise's specific requirements, without substantial investment in software and consultancy services. This is a cost-effective approach that is affordable by smaller firms. In particular, the author analysed two major components of ERP re-configurable objects: material or inventory objects and financial objects; their key relationship and the methods associated with the logistics and information flow of these components are explained below.

2. Integration using object-based model

In object technology, manufacturing can be considered as "information processing" and, as such, a database management system (DBMS) that can cope with the requirements of the data flow of material and financial objects among various processes is crucial to the running of the day-to-day operations of the organization. While manufacturing data are becoming more complex with more data types, the relational data model, which has been widely adopted by DBMS software tool developers in the past, has remained basically unchanged. Popular DBMS packages such as Oracle and SQL embrace the relational database concept for the development of their products without making significant changes to cater for SMEs. Although major DBMS developers have released packages that support more complex data files, these packages are based on the relational database model concept, which is fundamentally designed to handle data tables linked together through relationships. On the other hand, the object DBMS has been under research in the past years (Booch, 1991; Booch, 1996; Coad and Yourdon, 1990), and this research has identified its distinct advantage over RDBMS in terms of the handling of objects in the database, which can encapsulate attributes within the objects. Some ERP software packages based on the object technology concept have been developed recently, although the attention they have received does not match the requirements of SMEs in terms of the costs and maintainability of the products themselves. ODBMS has the distinct features of reconfigurability and reusability, which are essential in order to enable manufacturers to shorten the time to market and gain a distinct competitive advantage. Apart from this, a system encompassing reconfigurable objects, which can simplify and reinvent manufacturing operations, can be derived using an object-based repository system created in accordance with the ODBMS concept. However, the inception of an object DBMS in an organization may mean that it has to change its business operations and procedures, causing concern that the new system may not be totally compatible with the old systems, most of which are designed to work with the relational data model. Hence there is an urgent need for a solution that adopts the benefits of object technology but can be implemented with relational data base schemas.

The essential feature of this object-based relational data base (OBRDS) ERP software is the integration of all the different information of an enterprise: various management functions are integrated into one system focused on logistics, finance and information flows. On the other hand, it can be considered as a best enterprise model, which is a reference model with a rational enterprise operational process and an enterprise organizational structure. It is a realization in software based on the workflow of an organization. For example, sale orders flow from customers to an enterprise, then to the vendor (order flow). Materials flow from the vendor to an enterprise, then to the customer (logistics). Money flows from the customer to an enterprise, then to the vendor (finance flow). Integrating the three flows efficiently is the primary objective of an enterprise. The optimizing, harmonizing and planning of the three flows are the main tasks of enterprise management. Integration and normalization are ways to achieve the goal; integration refers to the varying information in the enterprise logistics that can be reflected in the finance flow in real time. That is, the enterprise can monitor its varying operating status in real time by monitoring its finance flow. However, in reality, a company will need a certain period, such as one day or one week, to obtain the varying finance and cost information, because of the time taken for data collection and conversion.

2.1 The logistics and financial objects

In an enterprise, we can define the classes of objects related to logistics as material objects

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 779–786

(MO): these are the raw materials, work-in-progress (WIP) and finished goods. Financial objects (FO) are related to the accounting and monitoring of the organization's assets and values. In the valuation of raw materials, they can be considered as goods/materials received, and their actual cost can be calculated. WIP and finished goods yield estimated values because their real values depend on current prices and the corresponding costs in sales and overheads, etc. They are therefore considered as estimated costs. MO can be further divided into two parts: material with no physical changes (MWNPC) and material with physical changes (MWPC). MWNPC can be classified into MO with no position change (NPC) and moving MO (MMO). The former includes various kinds of raw materials, WIP and finished goods in a static state. The latter includes raw materials, WIP and products that are moving from one value-added working center to the next, or to the inventory.

The accounting and measurement of an enterprise is very often carried out at various points or positions in the logistics. The set of MO with NPC consists of the static quantity and value distributions: the number of MO will not change within a certain period of time. On the other hand, MMOs are dynamic: the changes in their positions in logistics result in the changes in the quantities and values in the corresponding points. MMOs can be divided into two parts. One part is moving inside the enterprise and we can determine its cost and value. The other part is moving outside the enterprise. MWPC is where there is value added; the ingredients of such material are difficult to measure because there are many factors such as re-work, rejections and cancelled orders. The MO with NPC are frequently those that enter in the inspection, temporary storage or inventory points. For example, raw materials in store are moved to production based on the part-list or BOM (bill of material).

In the accounting and measurement of enterprise logistics, the information system should reflect the real status of the enterprise in real time. Theoretically, MO values are always changing to reflect the changing market and thus need to be evaluated in real time. Each MO with NPC should correspond to at least one account. The static value distribution at each inspection point in the logistics in real time can thus be obtained by summarizing these accounts. Each MMO should correspond to at least two accounts: the inventory account that tracks goods/material issued and the inventory account that tracks goods/material received. The dynamic value distribution at each logistics point at a fixed interval can be obtained by summarizing all of the MMO. Each MWPC is an MMO (such as a raw material) at the time of leaving the inventory, and becomes a new MMO before it goes into another inventory (i.e. WIP or finished goods). The original value is vanished, and the new value is added: these are the measurements of the quantity of input and output of a MO in a given period, sharing the total expenses (including cost of materials, overheads and other expenses) among the products. Thus, it is the MO with NPC that an enterprise needs to measure and control. These MO will cause at least three accounting changes: accounts for good issue and good receipt, as well as the corresponding production accounts. Because the accounting information is very important to an enterprise, it must keep the corresponding accounts updated. In summary, we have defined two kinds of MO and their properties, and the theory of immeasurability:

- MWPC cannot be measured accurately because of the theory of immeasurability

According to the theory of immeasurability, the position and shape of the MWPC cannot be measured simultaneously. Its shape keeps changing (as in machine processing) when its position is measured and its position changes (as in transportation to the next work center or inventory). The theory is equally applicable to the other production and assembly stages. From the perspective of information management, the measurement of MWPC can be done at the two logistics positions where changes occur. However, due to the theory of immeasurability, an enterprise does not measure the MWPC because of the difficulties that we mentioned. Instead, we measure the quantity changes at the two logistics positions, often with some time delay. Thus, we can only estimate the MWPC using MO with no physical and no position change where there are inventories, WIP or finished goods. The changes in this logistics value can be calculated based on the position and integration of the MO and FO: obtaining the value/asset of the static MO in each logistics position of the finance flow, reflecting value/asset changes at each logistics position in the financial information when movement occurs. The former is relatively simple: it is the matching of the MO to the corresponding account. The latter is more complex: every movement has a different MO, a different direction, a different cause, and a different purpose for the inventory; each movement will affect the finance information flow. The following section further elaborates how these objects can be integrated in the OBRMS system.

3. Relating the object classes

There are many reasons and events that can cause or trigger MO movement. Such events can trigger

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 779–786

not only the movement but also the updating of the accounts. The ERP system should record the new position of the MO and the quantity changed in the corresponding logistics positions. In order to trigger these objects, we can use an event key such that there is always a reason for an MO to move in the enterprise logistics. That is, the movement is triggered by some events and results in corresponding changes of the MO in the inventory and the accounts. These can be inventory accounts, purchasing accounts, and so on. In a simple relationship-type database, we can use a two-dimensional table: we can define a movement object, which relates to the material objects in order to trigger the account objects. Table I illustrates how the objects can be related together:

This simple table is used to relate the material and movement objects with the event key. Therefore, the ERP system can identify the corresponding account based on the event key triggered. The disadvantage of this method is that there are too many types of material and movement objects, and corresponding logistics positions. Another approach is to introduce a material object and set up a valuation class to separate the MO. The valuation class belongs to the accounting object, and the movement object is the description of the movement type.

The relationships are therefore multiple: one MO can correspond to one or more kinds of valuation class, and vice versa. Both the material object and the movement object identify a unique event key, so the event key can be used as a trigger to update the account when the MO is moving.

The relationship between the event key and the valuation class can uniquely identify a set of accounts, and then integration between logistics and finance information can be done in real time, as shown in Figure 1.

The valuation class can be further divided into groups. Here, an event key can be identified uniquely by valuation group; the valuation group will contain several departments or units of an enterprise. Figure 1 shows an example where the attributes include tax rate, second level accounts and so on, i.e. the consumption description and the inventory description from the billing of goods received/issued of the corresponding MO. The consumption shows whether the material belongs to consumption/non-consumption material.

4. System design and implementation

Using the above principles, various ERP modules can be implemented. Basically, the ORDMS ERP system consists of a number of modules.

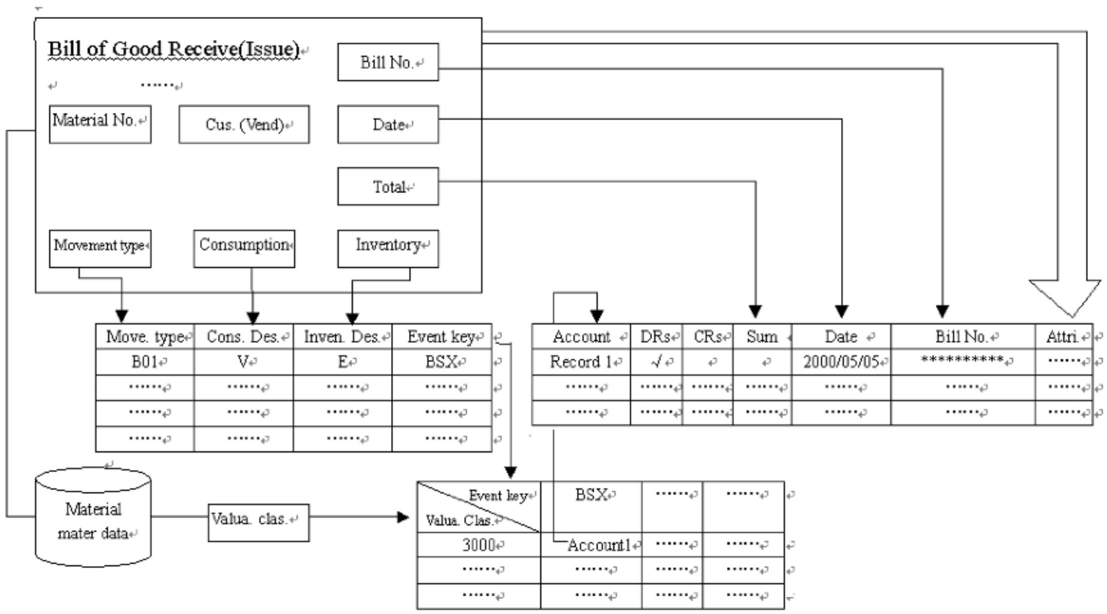
The essential feature is the reconfigurable object repository (ROR), consisting of the MO, the FO, the movement objects and the valuation classes, in which the events and triggers are used by these components to build an application for some specific workflow applications. These objects of different features as described in the above sections can be implemented using application development tools such as VB5 (Microsoft Corporation 2000a, b, c), Delphi (Calvert 1997; Henderson 1998) or Powerbuilder (Biberdorf *et al.* 1997). This reconfigurable object repository is the major component of the system. In fact, there are pure object-oriented database packages available on the market, such as Jasmine from Computer Associates (2003), with full capability to store objects in the database, embracing the capability to accommodate a wide variety of data types (text, image, audio, video) and relationships – a feature nearly impossible to support using a pure relational database model. However, these packages are often not affordable for SMEs, which have stringent budget constraints and the additional concerns of upgrading the hardware to meet the software requirements, and paying the maintenance service fee. Further, the existing computer systems operating in companies are mostly designed to work with relational data models, and companies' business will be at stake if compatibility problems occur after a pure object DBMS is deployed. In reality, the text data is used most of the time in areas such as BOM and inventory, and can thus be effectively handled by the proposed ORDMS. It is more economical for SMEs to build this database system, which can manage the attributes of the objects but still remains a relational database. As this OBRDS is fundamentally a relational database system enhanced to handle object data, it can be implemented by most Windows database development tools, such as Access and FoxPro.

In fact, the system we implemented uses Access2000 with VBA language (Microsoft Corporation 2002); this ORDBS ERP can be seen in Figure 2, and the basic modules are summarized below:

Table I Relating the material and movement objects

	Movement object			
Material object	**Goods received to inventory**	**Goods received to inspecting area**	**Goods issued**	...
Raw material 1	Event key 1	...	Event key 9	...
Raw material 2	Event key 1	...	...	
WIP	Event key 6	...	...	...
Product 1...	...			...

Figure 1 Using material object, movement object and valuation class



4.1 Purchasing and inventory module

The workflow of a typical purchasing process or RFQ (request for quotation) to place a purchasing order includes the quoting of vendor price, tender evaluation, drawing up a contract, etc. When the goods/materials are received based on the PO, they are then subject to inspection, invoice verification and accounts receivable.

4.2 Sales and distribution module

When the sales department issues the sales order (SO) to the customer who makes a contract with the company, a production plan is produced. The material/inventory is issued with the BOM for picking and packing the goods, and delivering them to the customer. The billing information after confirmation of shipment is used for accounts receivable in the accounting department.

4.3 Production module

A master production plan is used for MRP calculation and the results checked for material shortage. A work order is generated on the shop floor for production, from the issue of raw materials to the WIP and to inventory. In many manufacturing enterprises in China, this part of the ERP system is often done manually because of the difficulties in controlling lead times where subcontractors are commonly used.

4.4 Accounting module

The accounting module includes a general ledger, assets, consolidation, a special ledger, and so on. Among these, the account payable and account receivable operations can be implemented through a consolidation account. The material information from vendors will trigger the account receivable function automatically when the inventory supervisor completes invoice verification. Delivery to the customer will trigger the account payable function when the customer's bill is created. The little box at the bottom right of Figure 2 contains the valuation area and the valuation class information. When various types of MO move in the enterprise logistics, they are identified with their event keys and valuation class to trigger the corresponding account payable and account receivable functions.

Other than the basic modules of the ERP shown in Figure 2, for more complicated processes or a more complex industry, customization is required. The implementation of this model will be a little different because enterprises usually have to make changes to suit their particular workflow. Taking the sales process as an example, the typical steps begin with the customer: SO planning, good picking, billing, goods issue, as well as the updating of the account receivable. However, when the workflow of the goods issued and billing are reversed, and the account payable process is carried out only when there are multiple orders, the system must cater for changes in these workflows. From the business perspective, an enterprise can be considered as "virtual": it is a set of processes, and the degree of the process integration determines its operational efficiency. This integration enables the ERP software and Business Process Re-engineering (BPR) to reinforce each other. Moreover, the material objects and finance objects are considered as planning resources where there are changing

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 779–786

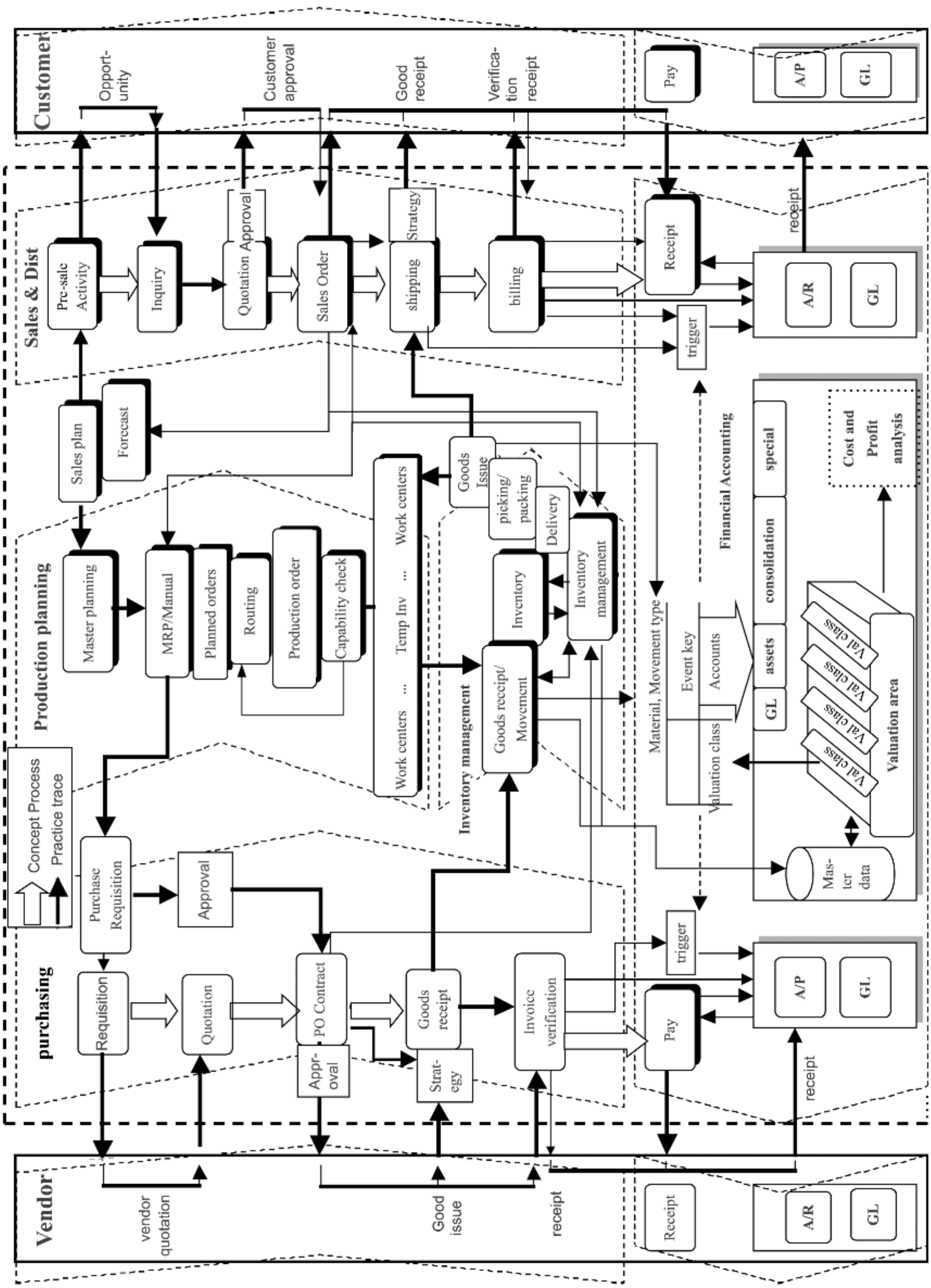


Figure 2 An OBDMS ERP model for SME

goods/materials received. For example, purchasing materials means materials purchased only when they are made payable; sales means goods sold only when they are made receivable. Hence, the following statement summarizes our general design principle in the production planning module:

- The WIP and inventory material are static in its logistics positions, and the integration between logistics and finance information is the operation of goods received and goods issued, which triggers the accounting objects.

In the implementation of the production module, the master production planning and MRP modules are therefore composed of an inventory of the current quantity in stock, and planning the future quantity to meet customers' requirements. The MO object does not necessarily go through the inventory, but we have to update its quantity in the corresponding account (i.e. virtual goods received). Based on the object design, this ERP model is flexible and can accommodate various enterprise workflows. The SAP "virtual organization" concept, as pointed out in earlier research by the author, can be achieved (SAP company 1999:2000, Ip and Chen 2002). In order to demonstrate the implementation results, the following provides a case study of SMEs and compares the process changes before and after implementation. The changes in workflow are illustrated using a typical PO procedure in this company.

Workflow before implementation when the purchasing department sends out a PO:

(1) When the goods and invoice arrive, the invoice is sent to the purchasing department and for the goods receipt is issued by the inventory/ store.
(2) The purchasing department inputs the invoice into the system using a copy of the PO, and the invoice then goes to the accounting department.
(3) The purchasing department issues the billing of goods received (BGR) and sends it to the inventory.
(4) When the goods enter the inventory, the inventory supervisor reads the BGR and identifies the name, quantity, and quality of the goods; if they match, invoice verification will be completed.
(5) The accountant uses the contents of the BGR to enter the accounting items in the journal, and posts them in the general ledger.
(6) Accounts payable makes use of the invoice, which is then sent to the general ledger after being audited.
(7) Each step in the above process requires audit and verification.

Workflow after implementation when the purchasing department sends out the PO:

(1) The purchasing department sends out the PO, which can be retrieved by the purchase, inventory and accounting processes.
(2) The purchasing information can be sent directly to the inventory when the goods and the invoice arrive.
(3) Goods received is done on line: the inventory supervisor inspects the name, specification, and quality of the goods, and tests whether they match the PO and the invoice.
(4) The inventory supervisor compares the quantity and the price of the invoice, item lists and PO; if they match, he proceeds with the invoice verification operation.
(5) When the invoice verification is made, the accounting information is updated automatically.
(6) The payment operation can be carried out by the accountant directly when there is an accounting item initiated after the invoice verification.

The following summarizes our findings regarding the difference in workflow after implementation. They reveal differences in management practice and organizational structure.

4.5 Integration represents different organizational structures

Before implementation takes place, the workflow follows a hierarchical structure: the structure cannot be flattened because inventory/material data is collected from each area, processed, integrated and entered into the corresponding account. In this case, the logistics and finance information cannot be synchronized: the accountant has not only the task of updating the accounts, but also the responsibility of verifying the transactions. Very often, this results in batch updating instead of real-time information.

The disadvantages are: decreasing the reliability of the data, increasing the workload of the accounting department, and delaying decision-making. On the other hand, the workflow after integration is flat. All information is shared at the same level, and the need for auditing is minimized: the accountant handles all related transactions, including accounts payable and accounts receivable.

4.6 The system provides better communication among departments

Before implementation, the goods received or issued included material name, payment terms, quantity, valuation class, inventory description and so on. This means that the BGR would involve at least three departments: valuation class belongs to the accounting department; payment terms,

materials and quantity involve the purchasing department; and the inventory supervisor is responsible for inventory items. Suppose there is a quality inspection at the inventory and there is a quality problem, so that the inventory supervisor needs to communicate with the purchasing department in order to identify a solution. As these departments do not share a common database, the information delay will result in the typical situation where the accounting processes are carried out only at month's end; thus the inventory costs, trading and manufacturing profits are not available in real time. After implementation, the inventory supervisor and purchasing department share the same information. When there is a problem with the PO, the purchasing department can take immediate action; when there is a problem in goods received because of quality rejects, the inventory supervisor can handle them effectively. Because the system is now integrated, any changes and cost can be measured in real time.

5. Conclusions

We have analyzed the characteristics of MO and FO in enterprise logistics. The design of an ERP system should effectively provide for integration of the two objects. An ERP system is developed using this approach; it is a simple system with its own organization and workflow suitable for many small and medium enterprises in China. These objects are a generalized class, which means that the model serves as a common template for the generation of business rules for different industries. The objects are related together to produce the ERP module (an object by itself). These objects reside in an Object Repository and form an Object Based Relational Data Base System, which contains records and includes the attributes of various objects. It has the advantage of workflow re-configurability and re-usability. The differences before and after implementation of the system in an SME are illustrated, and the results demonstrate a flattened organizational structure, better communication, and enhanced workflow reconfiguration.

References

Biberdorf, D., Glidden, K. and Powers, S. (1997), *Powerbuilder 5 How-to*, Waite.
Booch, G. (1991), *Object oriented Design*, Benjamin/Cummings Publishing Co. Inc., Redwood City, CA.
Booch, G. (1996), *Object Solutions: Managing the Object-oriented Project*, Addison-Wesley, Longman.
Calvert, C. (1997), "Delphi 4 Unleashed", SAMS.
Chen, D. and Vallespir, B. (1997), "GRAI integrated methodology and its mapping onto generic enterprise reference architecture and methodology", *Computers in Industry*, Vol. 33 Nos 2/3, pp. 387-94.
Coad, P. and Yourdon, E. (1990), *Object-oriented Analysis*, Prentice-Hall, Englewood Cliffs, NJ.
Computer Associates (2003), available at: www.cai.com
Davenport, T.H. and Short, J.E. (1990), "The new industrial engineering: information technology and business process redesign", *Sloan Management Review*, Vol. 31 No. 4, pp. 11-27.
Gartner Group (1990), "ERP: a version of the next-generation MRPII", Gartner group.
Greenbaum, J.M. (1993), "SAP's R/3 software suite: architecturing open, integrated software for distributed enterprises", *Open Information System*, pp. 3-16.
Hammer, M. (1990), "Re-engineering work: don't automate, obliterate", *Harvard Business Review*, Vol. 68 No. 4, pp. 104-13.
Henderson, K. (1998), *Delphi 3 Client/server Developer's guide*, SAMS.
Ip, W.H. and Chen, B.C. (2002), "Organization structure and enterprise modelling in ERP realization", *International J. of Networking and Virtual Organization*, Vol. 1 No. 2, pp. 170-83.
Li, H. and Williams, T.J. (2000), "The interconnected chain of enterprises as presented by the Purdue enterprise reference architecture", *Computers in Industry*, Vol. 42 Nos 2/3, pp. 265-74.
Microsoft Corporation (2000a), *Microsoft Visual Basic (2000a) Language Reference*, Microsoft Corporation.
Microsoft Corporation (2000b), *Microsoft Visual Basic (2000b) Programmer's Guide*, Microsoft Corporation.
Microsoft Corporation (2000c), *Microsoft Visual C++ (2000c), Programmer's Guide*, Microsoft Corporation.
Microsoft Corporation (2002), *Microsoft Access (2002), Programmer's Guide*, Microsoft Corporation.
Ng, K.C. and Ip, W.H. (1998), "The development of an enterprise resources planning system using a hierarchical design pyramid", *Journal of Intelligent Manufacturing*, Vol. 9 No. 5, pp. 385-99.
Ng, K.C., Ip, W.H. and Lee, T.C. (1999), "A paradigm for ERP and BPR integration", *International Journal of Production Research*, Vol. 37 No. 9, pp. 2093-108.
Object Management Group (1998), "COBRA 3.0. 1998", available at: http://nt.excite.com:80/news/bw
Paradigm Plus description as OSMOS OOAD tool (1998), available at: www.osmos.com/community/
Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F. and Lorensen, W. (1991), *Object Oriented Modeling and Design*, Prentice-Hall, Englewood Cliffs, NJ.
SAP company (1999), "Training material", SAP company.
Unisys and SAP (1998), "Enterprise application solutions", available at: www.marketplace.unisys.com/sap/

Further reading

Doumeingts, G., Ducq, Y. and Vallespir, B. (2000), "Production management and enterprise modeling", *Computers in Industry*, Vol. 42 Nos 2/3, pp. 245-63.
SAP company (2001), "R/3 4.6D system and online help", SAP company.
Taylor, D., Mischel, J. and Penman, J. (1997), "High performance Delphi 3 programming", Coriolis group.

Collaborative supply chain planning using the artificial neural network approach

Matthew Chiu and
Grier Lin

The authors

Matthew Chiu and **Grier Lin** are based at the Centre for Advanced Manufacturing Research, University of South Australia, Mawson Lakes, South Australia, Australia.

Keywords

Supply chain management, Neural nets, Manufacturing resource planning

Abstract

The purpose of this paper is to show how the concepts of collaborative agents and artificial neural networks (ANNs) can work together to enable collaborative supply chain planning (SCP). An agent-based supply chain network is decomposed into multiple ANNs in a way that the actual customer requirements and the agents' goals and constraints are matched in different stages. An error-minimising algorithm which models the agents' collaboration mechanism is used to train three ANNs, namely the supply net, the production net and the delivery net, for pursuing complete order fulfilment across the supply chain. In the example problem, the collaborative SCP paradigm is applied to determine the supply plan of an alliance of small firms, which provides assemble-to-order goods with short delivery lead-time to a regional market. The calculation results showed that the ANN approach achieved complete order fulfilment and significantly increased the resource utilisation of all supply chain agents.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/1741-038X.htm

1. Introduction

The role of manufacturing operations is migrating to a task of final assembly, with increased reliance on supply chain partners who have differing objectives, perspectives and processes. The trend toward effective interconnection and collaboration between supply chain constituents has been long recognised as a key challenge in supply chain management (SCM). Much research effort of the field has been directed toward developing operations models and technologies that enables us to rebuild the manufacturing supply chain with greater alacrity and flexibility.

Distributed SCM is required to overcome the latency of centralised management. Effective supply chain collaboration requires the ability to establish functioning alliances, which can be formed and dissolved quickly in order to tackle rapid changes in demands and emerge new opportunities. When customer demand as well as production and distribution lines are frequently changed, it becomes necessary to endow every supply chain constituent to adjust its plan autonomously and at the same time to consider the optimum as a whole. Such an autonomous decentralised SCM model can be realised by an agent-oriented system. The autonomous agents are able to identify what are the customer requirements to be fulfilled. Then, they can cooperate, coordinate and negotiate with each other to agree on a common goal, while each agent can still ensure its own welfare being satisfied.

This paper proposes the application of the agent concept and the artificial neural network (ANN) approach to formulate a paradigm of collaborative supply chain planning (SCP). The rest of this paper is organized as follows. Section 2 explains the background and motivation of the research. Section 3 briefly reviews the principle of agent-oriented supply chain model and the auction mechanism for distributed SCM. Section 4 explains how the ANN approach works well alongside the concept of collaborative agents. In Section 5, we describe the supply chain network formation. In Section 6, we compare the two collaborative planning mechanisms including the auction mechanism and the ANN approach. Finally, in Section 7, some concluding remarks and ideas for future research are presented.

2. Background

The manufacturing industry is continuously looking for effective models for managing supply

Received: 2 July 2003
Accepted: 3 March 2004

DOI 10.1108/17410380410565375

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 787–796

chains. The sound manufacturing philosophies adopted today include the lean manufacturing which is a systematic approach to identify and eliminate waste through continuous improvement and the just-in-time that aims at supplying the right products to the right place at the right time and right amount. The sophisticated information systems used by manufacturing enterprises include enterprise resources planning (ERP) and advanced planning and scheduling (APS). Nowadays, the dynamic in market requirements and the globalisation of production have intensified the need for new modelling tools to design and manage complex supply chain networks which must be agile and re-configurable.

In the Internet-enabled supply chain network, the flow of information can be done in a many-to-many manner and on a real time basis. This information network can help synchronise the customer orders, the production schedules and the procurement plans of raw materials. To pursue complete order fulfilment across the supply chain, a supplier should correspond with its marginal lead-time to ship the raw materials or components, a factory should fabricate its products within the time bucket, and a distribution centre should use the fastest channel to deliver the finished goods to the consumers. This optimum supply plan needs to be formulated based on the constraints of every interconnected process. Mainstream commercial SCP solutions often adopt a centralised approach to collect massive data from the sites into a central database, e.g. the ERP system, and a network model together with mathematical programming methods to compute the optimum, e.g. the APS software (Knolmayer *et al.*, 2001). A dominant player of a supply chain can use the centralised planning system to impose operational policies on its upstream and downstream sites. However, there is limited space for the suppliers and distributors to make the same level of participations in the SCP process. The characteristics and constraints of each site may not be well represented in the network model. The suppliers and distributors may be assigned with targets that they are not able to meet within the specified timeframe. As a result, it triggers disruption to the supply chain network.

In these situations, the SCP process should be handled collaboratively. What required is an autonomous decentralised planning system, which allows each supply chain constituent to aim at its desired plan autonomously and at the same time to consider the global benefit. The decentralised SCP system should be built on an agent-oriented architecture with distributed artificial intelligence which enables each agent to consider its own characteristics and constrains and at the same time to pursue the optimum as a whole.

3. Agent-oriented supply chain model

The model proposed in this paper is based on the concept of collaborative agents. The research objective is to realise a collaborative mechanism for SCP. Nwana and Ndumn (1997) considered that collaborative agents should possess a combination of properties including autonomous, adaptive and coordinative. In other words, collaborative agents are capable of acting without direct external intervention, learning to change their behaviour, and coordinating with other agents to reach mutually acceptable agreements. The motivation of having collaborative agents systems aligns with the goal of distributed artificial intelligence in the following areas:

- providing solutions to inherently distributed problems;
- solving problems that are beyond the capabilities of one centralised system;
- enabling system components to learn and evolve;
- facilitating interoperation of heterogeneous intelligent systems.

The IT consulting firm, Cap Gemini Ernst & Young, predicated that a new generation of SCM software is being created with the agent technology (Cichowlas and Herneth, 2002). In the future system, numerous agents are implemented to represent every supply chain components. Collaborative agents interconnected by a network can work better than a centralised system trying to weigh the options and choose the best solution. The intelligence for achieving optimisation lies in the interaction of agents with algorithms based on natural systems such as ant simulation, swarm intelligence, genetic algorithm and neural computing.

The agent-based software architecture for managing the supply chain can support complex cooperative works and the management of uncertainties at the tactical and operational levels (Fox *et al.*, 2000). When designing a multi-agent supply chain system, agent decomposition allows the use of more sophisticated planning, scheduling and coordination methods to improve the overall quality of SCM. In addition, the dynamics of supply chain functions can be handled effectively by taking both local and global criteria into account. In dealing with stochastic events, collaborative agents will competently relax a subset of constraints in order to further optimise the goals at hand. Integration of distributed intelligence can

be achieved by opening up an agent's knowledge so that each agent is aware of and can access the functional capabilities of other agent.

An obvious problem related to decentralised SCM, is that of reaching agreements in a society of self-interested parties. In an agent-based system, an autonomous agent is allowed to maximise its own good with the highest priority. On the other hand, it is required to interact with other agents with which it may well not share common goals. Straightforward coordination policies such as first-come first-served, priority-first and combinations do not generally give a network-wide optimal solution. For examples: the first-come constituent supply chain agent may not be the one which can provide the best outcome for all; and some agents may specify maximum priority for whatever they are interested in. In the most extreme scenario, this may end up in a zero-sum encounter. In other cases, an outcome may be obtained with some agents being made worse off. But still in many situations, there is some potential for agents to reach mutually beneficial agreements on matters of common interests. Typical methods for multi-agent coordination include auctions, voting, bargaining, market mechanisms, contract nets, and coalition formation (Sandholm, 1999).

The use of auctions for reaching agreements between agents have been widely studied (Wellman *et al.*, 2001; Walsh *et al.*, 2000; Kaihara, 2000; Fan *et al.*, 2003). The auction mechanism is decentralized in the sense that each agent calculates its own bidding strategy based on prices derived through a distributing bidding protocol. As a result of competition, the auctioned item (goods, task or resource) is allocated to the agent who offers the highest rated bid. Common types of auction include: English auctions in which the item is allocated to the agent offering the first-price through rounds of open-cry bidding in an ascending price mode; Dutch auctions which are open-cry descending auctions; first-price sealed-bid auctions in which the participating agents are not able to see what every other agent is bidding and the item is awarded to the agent who submits the highest bid in a single shot; and Vickrey auctions which are second-price sealed-bid auctions (Wooldridge, 2002). A computational model for multi-tier auction based on the ANN approach is discussed in Section 4.

4. Artificial neural networks role

Our aim is to benefit from the feature of ANNs that provides a computational framework for solving combinatorial optimisation problems while considering many constraints simultaneously (Ramanujam and Sadayappan, 1995). An ANN is a network of interconnected computing nodes, which interact with one another via connection weights. In a multi-tier ANN, the computing nodes are partitioned into one input, one output, and one or more hidden layers. The function of an ANN is to produce an output pattern when presented with an input pattern. Training in ANNs is the process of adjusting the matrix of connection weights to reach the state that the correct output pattern can be obtained. The multi-tier network structure together with the training algorithm allows an ANN to model the coordination mechanism of an agent-oriented supply chain network. Solving a collaborative supply chain problem on an ANN requires a mapping of the problem onto the ANN in such a way that the solution can be decoded from the computing nodes' outputs and connection weights. The most straightforward scheme is to use one computing node for each agent. It is easy to understand and easy to implement since the ANN topology mirrors the supply chain network structure. Each node is set to transform its inputs (I) from other nodes to an output (O) according to an activation function (f), for example:

$$O_j = f_j\left(\sum_i W_{ji} I_i\right)$$

where

$$I_i = O_i = f_i\left(\sum_h W_{ih} I_h\right)$$

In the logic of auction setting, the node j is the auctioneer and its input nodes are the bidders. Agents with similar functionalities are grouped in the same layer of nodes to represent a tier of supply chain constituent. This multi-tier structure is extended into a chain-like system of agents, which are brought together to fulfil an end-customer demand. For example, the node j may bid to get the main contract from the node k in a higher tier and, in effect, the node i bids for the sub-contracts. The connection weights (W) represent the constraints and capacity of an agent to bid and the activation function denotes the agent's bidding strategy. Hence, it is possible for every agent to implement a unique bidding strategy as the means to manage its constraints and capacity in an agent-oriented supply chain network.

The training algorithm allows the supply chain network to impose winner determination scheme: which agent gets the auctioned item. An ANN can be trained with data of the customer requirements. When the goal is set to achieve 100 per cent order

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 787–796

fulfilment, the training is terminated if the nodes and their connection weights have developed an internal representation, which can match the reconstructed input (i.e. the auto-associated output) to the training data. This result can be achieved by gradually adjusting the connection weights to reduce the output error, for example:

$$\Delta W_{ji} = R_j \times (T_j - O_j)$$

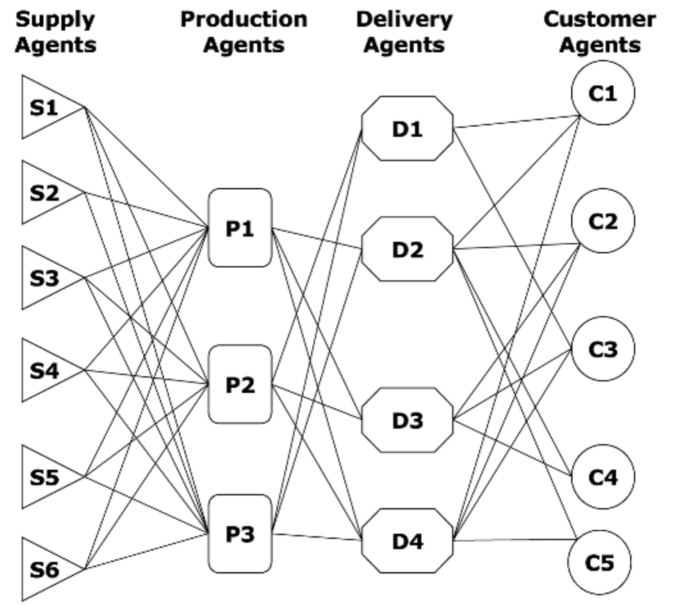
where R is the learning rate of the node j; T and O are the desired and actual outputs of the node j, respectively.

The choice of error-minimizing training method is justified with our aim to introduce a collaboration mechanism instead of setting up nodes to compete in a winner-take-all fashion. First, the output layer of an ANN, which represents the tier of customer agents, drives a virtual market mechanism, and the ANN propagates the output errors backwards to correct the supply plan of the supply tier until a general equilibrium is reached. Secondly, the error correction mechanism resembles the bargaining process and coalition formation between agents, and the agents search for a mutually acceptable agreement by adjusting the offers to one another. Finally, the training algorithm can be modified so that the learning rate of each node can be individually adjusted to reflect its operational constraints in the collaborative scheme, e.g. reducing the connection weight of a node at a faster rate if the connection cost is relatively higher.

5. Supply chain network formation

The proposed supply chain model is applied to determine the supply plan for assemble-to-order goods with short delivery lead-time in a regional market. The supply chain network shown in Figure 1 represents an alliance of small firms selling personal computers (PCs) in five locations. One of the alliance's aims is to establish a strong market position so that they can bid for supply contracts which, otherwise, they are not individually qualified to participate in. Another goal is to reduce the internal cost of the supply chain network for achieving a competitive advantage against large manufacturers of branded PC. These small enterprises are characterised by their alacrity and flexibility in offering customised PC configurations to consumers. Based on the negotiation protocol of the coalition, all supply chain members are able to attain reasonable profits and share the common stake of sustaining the supply chain network.

Figure 1 Agent-oriented supply chain network



In our study, the supply chain model contains four types of agents: customer, supply, production and delivery. This assemble-to-order production model relies on the customer agent, that functions as the sales representative of the supply chain to pass the customer requirements to the supply agent, that functions as the merchandiser of the supply chain. This arrangement effectively creates a virtual link between the customer and the supplier of raw materials and components, or establishes a prime link if the customer agent is implemented as an online ordering system. Therefore, once a customer specifies the PC configurations and places a purchase order, the supplier agent that serves the order can source the components and initiate the production cycle. This model provides two-fold benefits: processing discrete orders for delivery of custom lots down to individualized orders, and eliminating the production agents' component inventory so that the components can be changed to meet the customer specifications as fast as the PC technology is updated. Each type of agent has different tasks and goals as follows:

- The customer agent is responsible for acquiring order requirements from customers, negotiating with customers about prices and due dates, and consolidating and relaying the requirements to all supply agents in the supply chain network. Each customer agent in the supply chain network has a primary goal of 100 per cent order fulfilment, so it must seek for suitable supply agents who can meet its mission. The sales revenue from a customer

order is shared between the customer agent and its supply agents.

- The supply agent is able to recognize what customer orders to be fulfilled and figure out what needs to be supplied to the customer agent. A supply agent aims to obtain the customer orders of higher revenue, while it needs to find the best production and delivery partners who can meet its delivery commitment with less operational costs.
- The production agent represents the factory where the final products are assembled. Its goal is to make the best use of the production capacity and keep minimal inventory. A production agent only accepts raw materials or components from a supply agent on the condition that every item made is sold to consumers. The profitability of a production agent mainly depends on the end-to-end savings of the manufacturing and logistics operations across the supply chain.
- The delivery agent is responsible for providing suitable channels to dispatch the finished goods to consumers. Minimising logistics costs is of the most important concern, as the operational savings contributes to the revenue of a delivery agent.

An example problem for the supply chain network shown in Figure 1 is considered as follows:

- Five customer agents (C1-C5) provide the customer requirements of quantity and delivery to the supply chain network which contains six supply agents (S1-S6), three production agents (P1-P3) and four delivery agents (D1-D4). The supply agents are well aware of the customer requirements as well as the characteristics and constraints of the production and delivery agents. This can be achieved by exchanging messages between the agents through an information network (Finin *et al.*, 1997). This study of inter-agent communication languages will not be discussed in this paper.
- The supply agents provide the computer modules, e.g. motherboards, power supply units and peripherals; the production agents assembly the computer systems; and the delivery agents handle all shipments of final products.
- The operational characteristics and constraints of each agent are listed in Tables I-IV. The maximum output of the supply network is determined by the combined capacity of all supply agents, as it is relatively easier to acquire additional production and delivery resources. In this regard, the tier of supply agents acts as the focal company of the supply chain network.

Table I Customer requirements

Customer agent	Required quantity (unit)	Delivery requirement (day)	Profit ($)
C1	120	7	70
C2	200	7	72
C3	300	12	67
C4	120	6	80
C5	110	7	75

Table II Capacity of the supply chain network

	Capacity (unit)
Supply agent	
S1	100
S2	300
S3	200
S4	150
S5	50
S6	80
Production agent	
P1	320
P2	220
P3	340
Delivery agent	
D1	330
D2	170
D3	190
D4	190

Table III Delivery lead-time of the supply chain network

Lead-time (day) From			To		
	P1	*P2*	*P3*		
S1	2	2	1		
S2	4	X	3		
S3	3	2	3		
S4	X	2	2		
S5	1	X	1		
S6	1	1	1		
	D1	*D2*	*D3*	*D4*	
P1	X	1	2	3	
P2	1	X	X	3	
P3	1	4	X	5	
	C1	*C2*	*C3*	*C4*	*C5*
D1	1	X	2	X	X
D2	1	2	X	2	1
D3	X	2	2	1	X
D4	2	3	5	X	2

Note: X – no connection between the two agents

6. Comparison of collaborative planning mechanisms

In this section, we compare the agent-based auction mechanism with the ANN computing

Table IV Operational savings of the supply chain network

Cost ($ per unit) From	To				
	P1	*P2*	*P3*		
S1	9	12	4		
S2	18	X	17		
S3	12	10	18		
S4	X	8	10		
S5	6	X	5		
S6	5	4	6		
	D1	*D2*	*D3*	*D4*	
P1	X	6	10	13	
P2	7	X	X	14	
P3	6	18	X	23	
	C1	*C2*	*C3*	*C4*	*C5*
D1	6	X	12	X	X
D2	4	11	X	12	5
D3	X	10	13	5	X
D4	10	16	20	X	8

Note: X – no connection between the two agents

model in analysing the following typical problems of collaborative SCP:

- The supply chain network must achieve 100 per cent order fulfilment in order to avoid loss of sales.
- The supply agent needs to determine the quantity of parts that should be provided to its production agents for serving a particular customer order.
- The supply agent needs to ensure that its production and delivery agents can have the capacity to meet the delivery schedule specified by the customer agent.
- The supply agent targets to get the orders which are more profitable and fulfil the orders with lowering production and delivery costs.

6.1 Drawbacks of the auction mechanism

Using the English auction mechanism as discussed in Section 3, the supply agents can compete for the orders from the customer agents in the supply chain network. As shown in Table V, the supply chain routes are selected in order to achieve the highest possible profits and savings. To begin with, the customer agent C3 selects the supply agents S2 and S4 routing through the delivery agent D4 that is at 100 per cent loading with 190 units. Similarly, the backlog of 110 units is assigned to the route through the delivery agent D3. Following the profits-savings ranking, the customer agent C4 chooses the route proposed by the supply agent S3. As the remained capacity of the production agent P1 and the delivery agents D2 and D3 cannot cope with the order from the customer agent C2, just 50 per cent of the required quantity can be fulfilled. Finally, only the routes through the delivery agent D1 are available to serve the customer agent C1, and the supply agents S1 and S2 are selected because of the capacity shortfalls with the supply agents S3, S4 and S5.

Although the auction mechanism can resolve the supply chain routes that individually offer higher operational savings, the supply chain network cannot achieve its primary goal of 100 per cent order fulfilment. Worse than the shortage of 100 units for the customer agent C2, no supply is available to the customer agent C5. In contradiction to this insufficient situation, the capacity of some agents is under utilised including the supply agent S6 serving no customer order, 90 per cent productivity of the production agent P2 staying idle, and 65 per cent resource of the delivery agent D1 being surplus.

6.2 Application of the ANN approach

The supply chain network is decomposed into multiple ANNs in a way that the actual customer requirements and the agents' goals and constraints are matched in different stages. Three ANNs, namely the supply net, the production net and the delivery net, are used. In the first stage, the ANN computing model is applied to map the supply resources to the customer orders. The second stage is to allocate the production resources to the customer orders taken by each supply agent. The final stage is to identify the delivery partners for the supply and production agents so that suitable supply chain routes are formed to satisfy the customer requirements with less operational costs.

6.2.1 Allocation of customer orders in the supply net

The first ANN contains three layers of computing nodes employing the linear activation function. The input and output layers (C_i and C_o, respectively) represent the customer agents, and the hidden layer (S) denotes the supply agents. The training algorithm is applied to find the matrix of connection weights (W) in the following equations:

$$[S] = [W][C_i] \text{ and } [C_o] = [W]^{-1}[S]$$

where

$$[C_i] = [C_o] = [120, 200, 300, 120, 110] \text{ and}$$

$$[S]^T = [100, 300, 200, 150, 50, 80]$$

Aiming at a maximum yield, a supply agent prioritises its bids according to the amount of sales revenue. In contrast, in order to assure the delivery promise, a customer agent rates the bids from its supply agents on the basis of shorter delivery time. Therefore, a collaboration policy is imposed to

Table V Collaborative planning by the auction mechanism

Supply chain route	Profits plus savings ($ per unit)	Route lead time (days)	Available route capacity (units)	Supplying quantity (units)
Required quantity for C3: 300 units				
S4-P3-D4-C3	67 + 53	12	150	150
S2-P1-D4-C3	67 + 51	12	190	40
S5-P3-D4-C3	67 + 49	11	50	0
S6-P3-D4-C3	67 + 48	11	80	0
S1-P3-D4-C3	67 + 47	11	100	0
S3-P1-D4-C3	67 + 45	11	190	0
S2-P1-D3-C3	67 + 41	8	190	110
Required quantity for C4: 120 units				
S3-P1-D2-C4	80 + 30	6	170	120
S1-P1-D2-C4	80 + 27	5	170	0
S5-P1-D2-C4	80 + 24	4	50	0
S6-P1-D2-C4	80 + 23	4	80	0
Required quantity for C2: 200 units				
S5-P3-D2-C2	72 + 35	7	50	50
S2-P1-D2-C2	72 + 35	7	50	0
S6-P3-D2-C2	72 + 34	7	50	0
S1-P3-D2-C2	72 + 33	7	50	0
S3-P1-D3-C2	72 + 32	7	50	50
Required quantity for C1: 120 units				
S3-P3-D1-C1	70 + 30	5	0	0
S2-P3-D1-C1	70 + 29	5	100	100
S1-P2-D1-C1	70 + 25	4	100	20
S4-P3-D1-C1	70 + 22	4	0	0
S5-P3-D1-C1	70 + 18	3	0	0
S6-P2-D1-C1	70 + 17	3	80	0

prevent a supply agent from bidding for a customer order if the minimum lead-time of its supply chain is longer than the customer delivery requirement. For instance, the minimum lead-time from S4 to C2 is eight days, so S4 is not eligible to serve C2 who requires a delivery promise of seven days. The initial values of the weight matrix are given in Table VI.

The error produced by the initial weight matrix is minimised by decreasing the connection weights to C4 and C5, and increasing the connection weights to C1, C2 and C3. With supplies more than the customer requirements, the customer agent C4 imposes the winner determination scheme to select the supply agents S5 and S6, because the lead-time of these two agents is shorter than that of S1 and S3. Similarly, the customer agent C5 chooses S2 and S3. Therefore, the connection weights between these pairs of customer and supply agents are reduced to zero, while the remained connection weights are adjusted in proportional to the error associated with each node. In each round of weight modification, a supply agent is allowed to bid for the unallocated customer orders with its surplus capacity. The error-correction rules enable each agent to promote its stake in the supply net.

Table VI Initial values of the supply net's weight matrix

	C1	C2	C3	C4	C5
S1	0.00	0.00	0.00	0.83	0.00
S2	0.00	0.95	0.00	X	1.00
S3	0.00	0.00	0.00	1.00	0.73
S4	0.33	X	0.00	X	1.00
S5	0.00	0.00	0.00	0.42	0.00
S6	0.00	0.00	0.00	0.67	0.00

Note: X – no acceptable link between the agents, connection weights fixed at 0

The supply net successfully shares the customer orders after three rounds of weight adjustment. The results are: S1C2(100), S2C3(270), S2C5(30), S3C2(90), S3C5(80), S4C1(120), S4C3(30), S5C4(50), S6C2(10) and S6C4(70), where the presentation format S1C2(100) represents the supply agent S1 furnishing the customer agent C2 with 100 units.

6.2.2 Allocation of resources in the production net

The second ANN contains three layers including the input, output and hidden. Each supply agent's allocation of the customer orders requires one computing node, i.e. ten nodes in each of the input and output layers. The hidden layer contains three nodes denoting the production agents.

In the production net, a supply agent aims to select its supply chain partners that can fulfil its inherited delivery commitment. Hence, bids from production agents are mainly rated on the basis of shorter delivery time. To increase profits, a production agent prioritises its bids according to the amount of operational savings. Three collaboration criteria include:

(1) a production agent must take the customer order if it is the only production resource in a supply route linking a particular pair of supply and customer agents;
(2) a production agent cannot bid for a customer order if the delivery lead-time of its supply route is longer than the customer delivery requirement; and
(3) a production agent can bid for additional customer orders if it has surplus capacity in each round of weight modification.

The initial weight matrix for the possible supply routing is given in Table VII. To reduce the output error, the connection weights to S2C3, S4C3 and S6C2 must be decreased, while the links to S1C2 and S4C1 must be strengthened. By eliminating the agents with longer lead-time, the value of the link between P1 and S2C3 is set to 0. Similarly, the connection weights from P2 to S4C3 and S6C2 are pruned. A new link between P1 and S1C2 is established and the connection weight from P2 to S4C1 is increased to 0.55.

The production net successfully allocated the resources after three rounds of weight adjustment. The results are: S1P1C2(70), S2P1C5(30), S3P1C2(90), S5P1C4(50), S6P1C4(70), S3P2C5(80), S4P2C1(120), S1P3C2(30), S2P3C3(270), S4P3C3(30) and S6P3C2(10), where the presentation format S1P1C2(70) represents the production agent P1 acquiring the materials from the supply agent S1 and furnishing the customer agent C2 with 70 units.

6.2.3 Routing in the delivery net

The final stage requires an ANN of three layers. Each of the input and output layers contains 11 computing nodes, each representing a production agent's allocation of the customer orders from its supply agents. The hidden layer contains four nodes denoting the delivery agents. In the delivery net, a supply route is not eligible if the route's lead-time is longer than the customer delivery requirement, so these links are pruned from the ANN. A delivery agent must take the customer order if it is the only delivery resource in a supply route, so the associated connection weights are fixed at 1. To increase their shared profits, bids are prioritised by a delivery agent and rated by a production agent based on the amount of operational savings. The initial weight matrix of the acceptable supply routes is given in Table VIII.

A training method similar to that of the supply and production nets is used to correct the output error. The following results are obtained after two rounds of weight modification, with 13 routes from the supply to customer agents:

- S4P2D1C1(30), S4P2D4C1(90)
- S1P1D2C2(10), S1P1D3C2(60), S1P3D2C2(30), S3P1D2C2(90), S6P3D2C2(10)
- S2P3D1C3(270), S4P3D1C3(30)
- S5P1D3C4(50), S6P1D3C4(70)
- S2P1D2C5(30), S3P2D4C5(80)

6.3 Analysis of results

By using the ANN computing model, all customer requirements were fulfilled in an orderly manner. The error-minimizing algorithm mapped the supply chain routes to the customer demands in a few steps. Contrasting to the auction mechanism for maximising an objective function, the ANN-based collaboration mechanism aims to obtain a balance between the global optimisation and the multi-criteria imposed by every agent. Each agent was given a chance to pursuit their best interest before reaching an agreement. As anticipated, the outcome would not be the best solution for maximising the total amount of operational savings for the supply chain network. In the case of 65 per cent order fulfilment rate, the auction mechanism achieved an operational savings of $24,850 which was 22 per cent, higher than that offered by the ANN computing model. However, more important than the operational savings is that, following through the ANN-based collaboration mechanism, the primary objective of 100 per cent order fulfilment was achieved by relaxing the constraints and self-interests of the supply chain members. From the calculation results, it is clear that the increase of profit by

Table VII Initial values of the production net's weight matrix

	S1C2	S2C3	S2C5	S3C2	S3C5	S4C1	S4C3	S5C4	S6C2	S6C4
P1	0.00	0.30	1.00	1.00	X	X	X	1.00	0.00	1.00
P2	X	X	X	X	1.00	0.84	1.00	X	1.00	X
P3	0.30	1.00	X	X	X	0.00	1.00	X	1.00	X

Note: X – no acceptable link between the agents, connection weights fixed at 0

Table VIII Initial values of the delivery net's weight matrix

	D1	D2	D3	D4
S1P1C2	X	0.14	1.00	X
S2P1C5	X	1.00	X	X
S3P1C2	X	1.00	1.00	X
S5P1C4	X	0.00	0.60	X
S6P1C4	X	0.00	0.00	X
S3P2C5	X	X	X	1.00
S4P2C1	0.25	X	X	0.67
S1P3C2	X	1.00	X	X
S2P3C3	1.00	X	X	X
S4P3C3	1.00	X	X	1.00
S6P3C2	X	1.00	X	X

Note: X – no acceptable link between the agents, connection weights fixed at 0

$15,450 justified the reduced operational savings of $5,467.

Some agents in the ANN model incurred minor surplus capacity including S3, P1, P2, D3 and D4, but this excess was much less than the idle resources with the auction mechanism. It is caused by their constraints in competition and limitations in interconnection with other agents. The supply net imposes constraints on the production net and, in turn, the production net limits the routing in the delivery net. In an extreme case, additional resources may be required to create a solution. Moreover, supplementary collaboration policies between two agents in the same tier are necessary for allowing them to shift the workload with one another rather than increasing the redundant capacity of individual agents. In an effective supply chain network, more resource agents with small capacity are preferred to improve the connectivity, as more nodes and links extend the number of routes in a network. Furthermore, better management of deadlock is one of the key topics for future research, as it can improve both the ANN model and the auction mechanism.

7. Conclusions

This paper has reviewed the agent-oriented supply chain model, and compared two collaborative SCP paradigms, namely the auction mechanism and the ANN approach, for determining the overall supply plan of a supply chain network formed by small enterprises. This supply chain network that realises an assemble-to-order system has the major benefit of eliminating the need for production inventory based on a set of coordination policies, which matches the customer demand with reconfigurable supply chain routes. Collaborative planning is required when the centralised SCP approach is not suitable, e.g. where there is no dominant player in a small dynamic supply chain network.

In the example problem, it was found that the auction mechanism can resolve the supply chain routes that individually offer higher operational savings as a result of winner-take-all competition. However, the supply chain network had to trade off in terms of poor order fulfilment and under utilised capacity. To improve the supply plan, the ANN approach was applied to balance the agents' workload and operational savings.

As an enhancement, the agent-oriented supply chain model and the ANN approach complement each other to realise a simple computational framework for mapping the supply, production and delivery resources to the customer orders. In addition, this computational framework allows the decomposition of a complex problem into less constrained sub-problems which can be solved relatively easier. By using multiple ANNs for the sub-problems, the agents' goals and constraints are matched in different stages to find the final solution. The calculation results showed that the ANN approach can achieve complete order fulfilment and significantly increase the resource utilisation rate of all supply chain agents. In future research of the agent-based supply chain systems, more ANNs can be used to tackle other customer requirements and agents' constraints in addition to the sales revenue, delivery lead-time, production capacity, and operational savings which have been studied in this paper.

References

Cichowlas, A. and Herneth, C. (2002), *Agent Technology: Next Generation Software For the Adaptive Supply Chain*, available at: www.ch.cgey.com/servlet/PB/show/1004860/Agent%20Technology%20for%20Adaptive%20SC_E.pdf (accessed 21 May 2003).

Fan, M., Stallaert, J. and Whinston, A.B. (2003), "Decentralized mechanism design for supply chain organizations using auction market", *Information Systems Research*, Vol. 14 No. 1, pp. 1-22.

Finin, T., Yannis, L. and Mayfield, J. (1997), "KQML as an agent communication language", in Bradshaw, J.M. (Ed.), *Software Agents*, MIT Press, Cambridge, MA, pp. 291-316.

Fox, M.S., Barbyceanu, M. and Teigen, R. (2000), "Agent-oriented supply-chain management", *The International Journal of Flexible Manufacturing Systems*, Vol. 12, pp. 165-88.

Kaihara, T. (2000), "Agent-based double auction algorithm for global supply chain system", *Proceedings of 26th IEEE International Conference on Industrial Electronics, Control and Instrumentation*, Nagoya, pp. 678-83.

Knolmayer, G., Mertens, P. and Zeier, A. (2001), *Supply Chain Management Based on SAP Systems: Order Management in Manufacturing Companies*, Springer, New York, NY.

Nwana, H.S. and Ndumn, D.T. (1997), "An introduction to agent technology", in Nwana, H.S. and Azarmi, N. (Eds),

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 787–796

Software Agents and Soft Computing: Towards Enhancing Machine Intelligence, Springer, New York, NY, pp. 3-26.

Ramanujam, J. and Sadayappan, P. (1995), "Mapping combinatorial optimization problems onto neural networks", *Information Science*, Vol. 82, pp. 239-55.

Sandholm, T.W. (1999), "Distributed rational decision making", in Weiss, G. (Ed.), *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, MIT Press, Cambridge, MA, pp. 201-58.

Walsh, W.E., Wellman, M.P. and Ygge, F. (2000), "Combinatorial auctions for supply chain formation", paper presented at the Second ACM Conference on Electronic Commerce, Minneapolis, MN, pp. 260-9.

Wellman, M.P., Walsh, W.E., Wurman, P.R. and MacKie-Mason, J.K. (2001), "Auction protocols for decentralized scheduling", *Games and Economic Behavior*, Vol. 35, pp. 271-303.

Wooldridge, M.J. (2002), "Reaching agreements", *An Introduction to MultiAgent Systems*, Wiley, New York, NY, pp. 131-7.

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 797

Reviewers April 2003-March 2004

- Tim Baines, Cranfield University, UK.
- Dentcho Batanov, Asian Institute of Technology, Thailand.
- Adil Baykasoğlu, University of Gaziantep, Turkey.
- Eric Bohez, Asian Institute of Technology, Thailand.
- Maurice Bonney, Nottingham University, UK.
- Nourredine Boubekri, Northern Illinois University, USA.
- Ashley Braganza, Cranfield University, UK.
- Neil Burns, Loughborough University, UK.
- Peter Burcher, Aston University, UK.
- Mike Byrne, Nottingham University, UK.
- Felix Chan, Hong Kong University, China.
- Bing Chuah, City University of Hong Kong, China.
- Chiuh-Cheng Chyu, Yuan Ze University, Taiwan.
- Ben Clegg, Aston University, UK.
- Binman Das, Dalhousie University, Canada.
- Graydon Davison, University of Western Sydney, Australia.
- Rob Dekkers, Technical University of Delft, The Netherlands.
- Rick Delbridge, Cardiff University, UK.
- Rexford Draman, St Edwards University, USA.
- Elsayed Elsayed, Rutgers University, USA.
- Richard Fung, City University of Hong Kong, China.
- David Gallear, Middlesex University, UK.
- Frank Gertsen, Aalborg University, Denmark.
- Ian Gibson, University of Hong Kong, China.
- Jose Gieskes, University of Twente, The Netherlands.
- Andrew Greasley, Aston University, UK.
- Angappa Gunasakaran, University of Massachusetts, USA.
- Abdel-Aziz Hegazy, Helwan University, Egypt.
- Fred Hewitt, Aston University, UK.
- Yasu Hirakawa, Science University of Tokyo, Japan.
- Chin Yin-Huang, Tunghai University, Taiwan.
- George Huang, University of Hong Kong, China.
- Paul Hyland, Central Queensland University, Australia.
- W H Ip, Hong Kong Polytechnic University, China.
- Pi Ji, Hong Kong Polytechnic University, China.
- Jessica Kennedy, Central Queensland University, Australia.
- Tarek Khalil, University of Miami, USA.
- Khairi Kobbacy, Salford University, UK.
- Ashok Kochar, Aston University, UK.
- Gloria Lee, Buckingham University, UK.
- Michel Leseure, Aston University, UK.
- Doug Love, Aston University, UK.
- Martyn Luscombe, Cranfield Innovative Manufacturing Ltd, Cranfield University, UK.
- Rodney McAdam, University of Ulster, UK.
- Bart McCarthy, Nottingham University, UK.
- Les Mitchell, University of Hertfordshire, UK.
- Shunji Mohri, Hokkaido University, Japan.
- Jan Ohlager, Linköping University, Sweden.
- Nan Shing Ong, Nanyang Technological University, Singapore.
- Kul Pawar, Nottingham University, UK.
- Luisa Pellegrini, Pisa University, Italy.
- Duc Truong Pham, Cardiff University, UK.
- Nipa Phojanamongkolkij, Northern Illinois University, USA.
- Rajesh Piplani, Nanyang Technological University, Singapore.
- Keith Popplewell, Coventry University, UK.
- Sham S Rahman, University of Sidney, Australia.
- Svetan Ratchev, Nottingham University, UK.
- Peter Sackett, Cranfield University, UK.
- Amrik Sohal, Monash University, Australia.
- Ron Sanchez, IMD, Lausanne, Switzerland.
- Nelson Tang, Aston University, UK.
- Lloyd J Taylor III, University of Texas of the Permian Basin, USA.
- Wang Xing Ming, People's University of China, China.
- Karen Windeknecht, Central Queensland University, Australia.
- Peter Wright, Celestica Limited, UK.
- Richard Yam, City University of Hong Kong, China.
- Mohammed Yasin, East Tennessee State University, USA.
- Mustafa Yurdakul, Gazi University, Turkey.

Literati Club

Awards for Excellence

Jan Olhager
Linköping Institute of Technology, Linköping, Sweden

and

Martin Rudberg
Jönköping University, Jönköping, Sweden

are the recipients of the Journal's Outstanding Paper Award for Excellence for their paper

"Manufacturing strategy and e-business: an exploratory study"

which appeared in ***Journal of Manufacturing Technology Management*** , Vol. 14 No. 4, 2003

Jan Olhager is a Professor of Production Economics at Linköping Institute of Technology, Sweden. He received a Master of Engineering in Industrial Engineering and Operations Research from the University of California at Berkeley and a PhD in Production Economics from Linköping Institute of Technology. He has authored two books; one on production and operations management, and the other on manufacturing planning and control (both in Swedish). He has published in international journals such as *European Journal of Operational Research*, *Integrated Manufacturing Systems*, *International Journal of Operations & Production Management*, *International Journal of Production Economics*, *International Journal of Production Research*, *International Journal of Technology Management*, *International Transactions of Operational Research*, *OMEGA*, and *Production Planning & Control*. He serves on the editorial board of Production Planning and Control, the editorial advisory board of the *Journal of Operations Management*, and on the editorial review board of *Decision Sciences and Production and Operations Management*. His research interests include manufacturing strategy, operations and supply chain management, flexibility, and modelling and analysis of production management systems.

Martin Rudberg is Assistant Professor of Transport Telematics at the Department of Science and Technology, Campus Norrköping, at Linköping University in Sweden. He earned his MS degree in Industrial Engineering and Management, and his PhD degree in Production Economics, both from Linköping Institute of Technology, Sweden. Dr Rudberg's research interests include supply chain management, operations strategy and manufacturing planning and control, and he has published his research in *International Journal of Production Economics*, *International Journal of Production Research*, *OMEGA*, *International Journal of Manufacturing Technology and Management*, and *Journal of Manufacturing Technology Management* (formerly *Integrated Manufacturing Systems*).

Note from the publisher

Management journals and more; Emerald Management Xtra launches in 2005

For 2005, Emerald Group Publishing Limited will be launching the world's largest collection of peer-reviewed business and management journals, Emerald Management Xtra. As well as more than 100 research journals, the Emerald Management Xtra collection also features independent reviews of papers published in 300 of the world's major English language business journals, plus a newly developed range of online support services for researchers, teaching faculty, academic authors and others.

Emerald Management Xtra will be sold on subscription, primarily to libraries serving business schools and management departments, with online access to research papers and faculty services networked throughout an institution.

Designed in consultation with an international working group of business academics, Emerald Management Xtra is intended to consolidate the library's position at the heart of a university's research and information needs. In addition to nearly 40,000 research papers published by Emerald journals over the past ten years, Emerald Management Xtra features help for aspiring authors of scholarly papers, advice on research funding, reading lists and lecture plans for academic teaching faculty, and an online management magazine for business students and teachers. An online, moderated information exchange will also allow interaction with other researchers internationally.

Helping academic institutions and business schools perform better

Input and advice from heads of research, and deans and directors of business schools have helped focus Emerald Management Xtra on academic productivity improvement and time-saving, which is seen as particularly useful given the increasing pressures on academic time today. Building on the success of the Emerald FullText collection, available in more than 1,000 business schools and universities worldwide, Emerald Management Xtra puts the latest thinking, research and ideas at users' fingertips.

"Already, 95 of the FT Top 100 business schools in the world subscribe to Emerald journals or the Emerald Fulltext collection" said John Peters, Editorial Director of Emerald. "We will find over the coming years that Emerald Management Xtra will be an essential part of any credible business school or management faculty. You can't get all Emerald management and library information journals in full and in their current volumes from anywhere else; you can't get the support services we offer to faculty and the academic community anywhere else. We can even help you plan your conference travel through the world's largest independent register of academic conferences in business and management, Conference Central. We developed Emerald Management Xtra by asking academics, librarians and directors around the world what their biggest challenges were, we then put solutions in place to address them".

Integrated search and publishing innovation

An important part of the Emerald Management Xtra collection is an integrated search facility of Emerald-published papers with Emerald Management Reviews, which features nearly 300,000 independently written summary abstracts from a further 300 of the world's top business and management journals. This allows quick and easy summary of the relevant management literature.

From 2005, both Emerald journals and Emerald Management Reviews will feature Structured Abstracts. A first in management publishing, structured abstracts provide a consistent structured summary of a paper's aims, methodology and content. Used successfully in many medical and scientific journals, structured abstracts allow a quicker assessment of an article's content and relevance, thus saving researchers time and effort.

Value

Emerald is already recognised as a world leader in offering value for money from its online

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · pp. 799–800

Journal of Manufacturing Technology Management
Volume 15 · Number 8 · 2004 · 799–800

collections. Research undertaken by a large US library purchasing consortium showed that the Emerald portfolio was "best value" of any publisher collection, based on the ratio of usage and downloads to subscription price.

Unlike most other publishers, the Emerald Management Xtra portfolio is entirely subject-specific – focusing just on business and management (whereas other publisher collections contain a diverse range of subjects in sciences, social sciences, arts and so on). This means that Emerald Management Xtra gives superb value to business schools and management departments, with no subject redundancy.

Emerald Group Publishing Limited

Established for more than 30 years, Emerald Group Publishing has its headquarters in the north of England, with sales offices in the US, Malaysia, Australia and Japan. Emerald was founded as Management Consultants Bradford, later MCB University Press, as a spin-off from the University of Bradford business school, by faculty and alumni, and has maintained a tradition of having academics, former and current, as key decision-makers and advisers.

Emerald journals are almost exclusively international in scope, with around 75 per cent of all authors coming from outside the UK.

More than 100 of the Emerald Management Xtra journals collection are traditionally peer-reviewed. The Emerald Management Xtra journals collection is completed by a small number of secondary digest titles and practitioner-focused magazine titles. Emerald Management Xtra includes long-established titles such as the *European Journal of Marketing*, *Journal of Documentation*, *International Journal of Operations & Production Management*, *Management Decision*, *Personnel Review*, *Accounting Auditing and Accountability Journal*, and the *Journal of Consumer Marketing*.

Emerald Management Xtra is available now. For more information contact: Rebecca Marsh, Head of Editorial, Emerald Group Publishing Limited, Toller Lane, Bradford BD8 9BY England. Tel: +44 1274 777700; E-mail: sales@emeraldinsight.com

Rebecca Marsh
Head of Editorial